International Correspondence Schools, Scranton, Pa.

A-C Motor Repair

By

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Transportation and General Engineering Department
Westinghouse Electric Corporation

Revised by

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6631B Part 2 Edition 1

International Correspondence Schools, Scranton, Pennsylvania

International Correspondence Schools, Canadian, Ltd., Montreal, Canada

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What This Text Covers . . .

Induction motors use either squirrel-cage or phase-wound rotors. Faults in squirrel-cage rotors are mainly mechanical; the only possible electrical fault is an open circuit, which may be detected by a growler test and then repaired. Phase-wound rotors may have lap-wound or wave-wound coils. The characteristics of lap-wound coils are explained in Part 1 of this text; here you will learn about the tests which determine electrical faults in lap windings. The windings are usually tested for grounds, open circuits, short circuits, coil reversal, and wrong number of coils.

The meaning of front pitch, back pitch, winding pitch, and short pitch of coils in a-c wave windings must be well understood. The twelve phase leads have an important role in identifying the type of wave winding, especially in determining the number of slots per pole per phase (SPP). The SPP values determine the pattern of winding and make it possible to use simplified connection diagrams together with connection tables and checking tables for each SPP value. Phase coils are easily recognized because of their extra insulation and, if used, should be placed at the end of pole-phase groups.

For easier winding of wave-wound rotors careful preparations must be made and the groups of coils must be arranged in piles. Most complication is caused by short-lead phase coils which have to be grouped properly before winding. The procedure of insulating the coils, placing the coils in slots, connecting the windings by clips, and finally banding the coil ends is explained in detail, and illustrated by several examples of actual winding jobs and applications of connection diagrams and connection and checking tables. A trouble chart for synchronous motors, listing faults and their remedies, is given at the end of the text.

A-C Motor Repair

PART 2

Detecting Defects in Rotors

Rotor Types

Importance of Rotor

1. The repair of stators for a-c (alternating-current) motors was discussed in Part 1 of this text. Now Part 2 explains the repair of rotors. The various types of rotors and the possible defects and remedies are discussed, and the procedure for rewinding is presented in the order actually followed in a motor-repair shop.

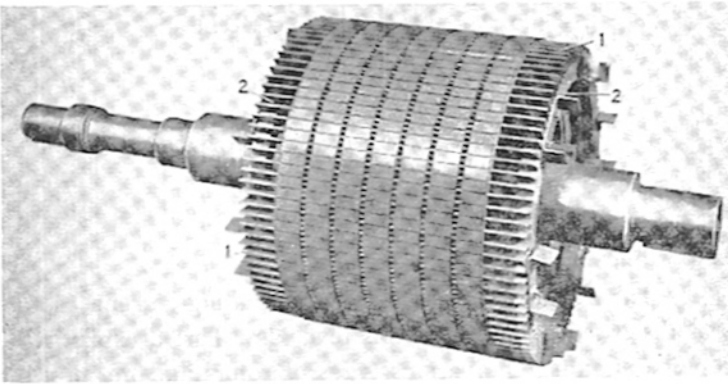
The rotor is the moving, or rotating, part of the a-c motor. It consists of the core and the conductors mounted on a shaft. The rotor of an a-c induction motor receives no current from the outside; the current in the rotor conductors is due to voltage induced by the magnetic lines of force which cut the conductors. The lines of force are those of a revolving field produced in the stator coils by application of an a-c voltage.

Many essential operating characteristics of an induction motor depend on the proper design of its rotor. The repairman, therefore, must understand the basic principles of the various types of rotors in order to make proper repairs without disturbing the electrical balance between the rotor and the stator.

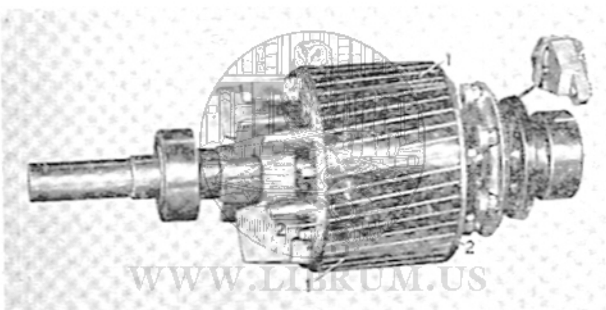
Squirrel-Cage and Wound Rotors

2. Rotors used in a-c induction motors are constructed either as squirrel-cage or wound rotors. Both types consist of a laminated iron core mounted on a shaft, but they use different types of conductors. The conductors are also called inductors, because they carry induced current.

The conductors of the squirrel-cage rotor are solid bars and form a grid, or cage, which accounts for the name of this type



(a)



(b)

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1. conductors, or bars
2. short-circuiting rings

(a) Rotor for large motor
(b) Rotor with cast rings and bars

FIG. 1. SQUIRREL-CAGE ROTORS FOR INDUCTION MOTORS

of rotor. The bars are short-circuited at each end of the rotor by short-circuiting rings.

The conductors of the wound rotor consist of wound coils, similar to stator coils. The coils are connected into phase windings and then to the slip rings on the shaft. External variable resistors are connected to the rings to close the path of the

induced current. The wound rotor is also known as a phase-wound rotor or a variable-resistance rotor.

Each of the rotor types has its advantages and preferred applications. The repairman should be familiar with the characteristics and possible defects of each type.

Construction of Squirrel-Cage Rotors

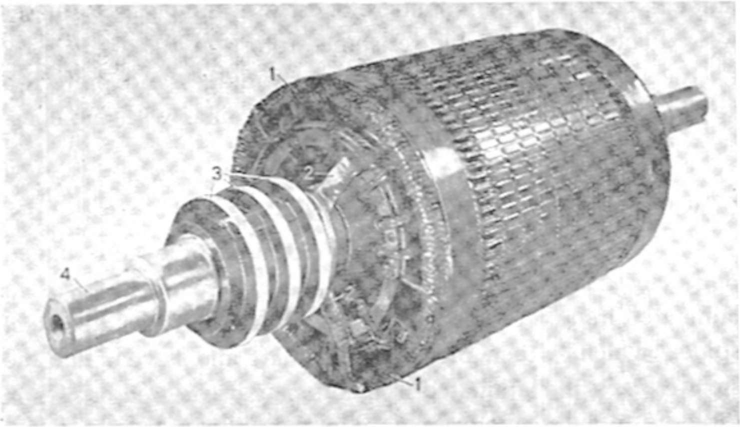
3. The modern squirrel-cage rotor is simple and rugged both electrically and mechanically. For the larger sizes, a laminated-iron core is assembled on a cast-iron or welded-steel spider, which is then pressed on a shaft and keyed. For the smaller sizes, the laminated-iron core may be pressed or shrunk directly onto the motor shaft. On the large rotor shown in Fig. 1*(a)*, the conductors *1* are solid bars; heavy end rings *2* short-circuit their ends.

Among the means used to fasten the bars to the end rings are bolts alone, solder alone, both bolts and solder, keystone construction, closed coils, welding and casting the end rings on the bars, as shown in *(b)*. The high operating temperatures of the rings are likely to loosen bolts or solder. The latest practice is to eliminate bolted and soldered joints completely, either brazing or welding the bars to the rings, or casting the complete conducting structure as one unit. When the conducting structure is cast as a unit, the metal is cast in place and special alloys are used.

High Resistance and Double Squirrel Cages

4. For intermittent service requiring high starting torque and only short running periods, such as hoist service, the cage, or grid, of the squirrel-cage rotor is made of high-resistance material.

Also available are squirrel-cage rotors with double grids, one with low resistance and the other with high resistance. One elevator company, for example, puts two complete grids on the same core; the outer one is of high resistance for start-



Courtesy of Westinghouse Electric Corporation

1. coils *2.* leads *3.* slip rings *4.* shaft

FIG. 2. WOUND ROTOR

ing and the inner one is of low resistance for running. The transfer of current from one to the other is automatic.

Phase-Wound Rotor

5. The phase-wound rotor shown in Fig. 2 has coils *1* wound into core slots in the same way as stator coils. The coil leads *2* are brought out and connected to three slip rings *3* on the shaft *4*. The slip rings are connected to a set of variable external resistors, (not shown), so that the resistance of the rotor circuit can be varied at will.

At the start, an increased resistance in the rotor circuit reduces the starting current for a given torque. If this increased resistance is not cut out during the operation of the motor, it reduces the operating speed. A reduction of the resistance increases the starting current and the speed.

The mechanical construction of the wound-rotor core is similar to that of the squirrel-cage rotor core; that is, the core consists of iron laminations mounted on the shaft.

The core of a wound rotor may have partly closed or open

slots, and the coils, like stator coils, may be lap wound or wave wound. Three or more slip rings are generally used.

The windings of wound rotors are practically always connected in three-phase star for three-phase and two-phase stators.

Lap Windings

6. Rotors with lap-wound coils have partially closed slots into which the coils are wound. For the coils, slot insulation, and methods of winding, the same general principles of construction and procedure are followed as outlined for stators in Part 1 of this text.

Wave Windings

7. Induction motors of appreciable size need large conductors to handle the heavy currents. As a result, the relatively small slot space available permits only a few turns in the coils. The wave winding is best adapted to these conditions and is now used extensively. The wave winding of an a-c rotor differs from that of a d-c (direct-current) armature. Since little information on a-c wave windings is available for repairmen, the major part of this text will be devoted to wave windings, their connections, and repair.

Repairing Squirrel-Cage Rotors

Mechanical and Electrical Faults

8. When any type of rotor is brought to a shop for repairs, it should first be inspected for mechanical defects, such as a bent or broken shaft, end play, a loose core, or unequal air gaps. Electric or gas welding and metal spraying are used to build up worn shafts, keyways, or other loosely fitting rotor parts. If correction of mechanical faults does not improve motor operation, a check for electrical faults must be performed.

Electrical Faults in Squirrel-Cage Rotors

9. Because the electric circuit of the squirrel-cage rotor is confined to the bars in the slots and the end rings, electrical faults are also limited to these parts. The end rings short-circuit all the rotor bars. Therefore, the induced current flows from a bar under a north pole of the stator to one end ring, through that ring to a bar under a south pole, and then back through the other ring to the original bar. An electrical fault not evident on visual inspection must be found through electrical tests with the current path just described kept in mind.

The main electrical faults in motors are a ground, a short circuit, an open circuit, or a wrong connection. Since the bars of most modern squirrel-cage motors are not insulated from their slots, there is, as a rule, no such thing as a ground. Because the rotor circuit by its very nature is shorted, a short circuit is not a fault.

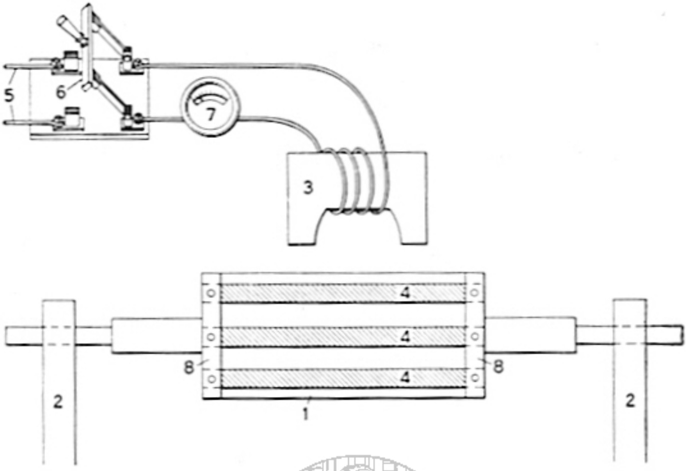
The bars of some rotors, both modern bars of high resistance and old types of low resistance, are insulated. If such bars become loose or grounded, those of low resistance need not be reinsulated; they may merely be tightened by driving in strips of sheet steel. All high-resistance bars, however, should be reinsulated with care, especially for elevator or hoist service.

There are also no faulty connections on squirrel-cage rotors because there are no coils to be connected.

Open Circuits

10. The only electrical fault possible in the grid work of a squirrel cage, other than a ground on a high-resistance bar, is an open circuit. The cause may be a break in a bar or an end ring, or failure of the contact between a bar or two and an end ring.

An open circuit in the squirrel cage would cause a low starting torque, heating of the stator and rotor conductors, and noisy operation. If the bond between an end ring and a



1. squirrel-cage rotor
2. stand
3. growler
4. bars
5. a-c source
6. switch
7. ammeter
8. end rings

FIG. 3. SETUP FOR GROWLER TEST FOR OPEN CIRCUIT IN SQUIRREL-CAGE ROTOR

bar becomes loose enough to permit a gap at that point, serious arcing will result, burning the rings. In testing the sound with a light hammer blow, any deviation from the characteristic ring of the metal means a break. This mechanical method, however, should be used merely to confirm the findings of the electrical test.

Growler Test

11. The growler test is the electrical method for detecting an actual open circuit in a squirrel-cage rotor or a poor connection between a bar and an end ring which may lead to an open circuit. The setup for this test is shown in Fig. 3. In this test the squirrel-cage rotor *1*, removed from its stator, rests on a wooden stand 2. To make the test, place the growler *3* on the rotor, above each bar *4* in turn, rotating the rotor as required. Connect the growler circuit to an a-c source *5* through the

switch 6. Read the ammeter 7 in the growler circuit as each bar comes under the growler. An open circuit or a high-resistance joint will lower the usual current considerably. When the ammeter reads low, examine carefully the bar under the growler, the parts of the end rings 8 in the circuit, and the connections between the bar and the rings.

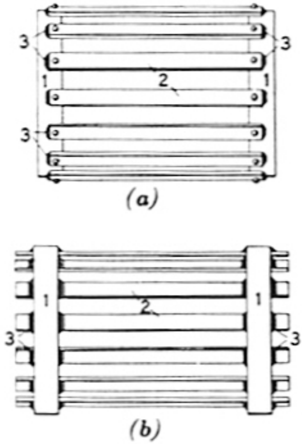
Welding, Soldering, and Brazing

12. A small fracture in an end ring may be welded shut. If it is too large for welding, both end rings must be replaced. In order to keep the same full-load speed, the resistance of any new rings must be the same as that of the old ones; an increase in resistance would lower the speed. If the connection between any bar and an end ring is loose or broken, proper soldering or brazing will remedy the trouble. Brazing is merely soldering, with brass as the repair metal instead of a lead or silver solder. Like brass, silver solder has a high melting point. A joint or ring repaired with either brass or silver solder will stand a higher operating temperature after the motor has been returned to service than will one repaired with lead solder.

The most frequent source of trouble in the squirrel-cage rotor is the bond between the bars and the rings. Only a man experienced in such work should make or repair such a joint. All old-type soldered or bolted joints should be brazed or resoldered with silver solder, whether or not the joints are defective at the time of checking.

Removing Rotor Bars

13. If any bar or end ring is cracked or broken, or if for any other reason a squirrel-cage grid must be replaced, the end rings should be broken at some point and then the joints between the bars and the rings should be heated with a torch. If the bars and rings are merely soldered or brazed together, the heat will soften the bond and the bars and rings may be pried apart. Any bolts or rivets, however, must first be re-



1. end rings
2. bars
3. brazing points

(*a*) Bars on top
(*b*) Bars underneath

FIG. 4. METHODS OF ATTACHING BARS TO RINGS

moved with a hacksaw, chisel, or cutting torch. A bar which lies in a partly closed slot must be driven out with the help of a steel drift.

Replacing and Reconnecting Rotor Bars

14. After removing a squirrel cage that is in bad order, take the dimensions of the defective parts and get new parts. It is usually most satisfactory to order replacements from the manufacturer, especially when the nameplate with its information is still on the machine to help the repairman identify the proper parts. When preparing the order, clean the rotor slots and make sure that the slots are still clean when you replace the bars.

If the squirrel cage of the rotor is constructed as in Fig. 1(*a*), put the new bars in place first, driving them in as required. Because no slot insulation is used with most rotors, and because loose bars in any rotor will cause vibration, the bars must fit the slots snugly. A good deal of careful hammering will therefore be necessary to get the bars into the slots

without damage to either the bars themselves or, more important, to the rest of the rotor.

The bars may be attached to the rings by the bar-on-top method, shown in Fig. 4*(a)*, or by the bar-underneath method, shown in *(b)*.

If the bars are laid on the rings, as in *(a)*, the bond should be strengthened by brazing on metal at the ends. Each end ring *1* offers a smooth surface to which the bars *2* are fastened mechanically and then brazed at the points *3*. A firmer construction is obtained by making the rings thicker and recessing them to receive the bars, then bolting or riveting the bars to the rings and brazing.

Sometimes the bar-underneath method, shown in *(b)*, is used. The end rings rest on the bars and enclose the entire bundle of bars but are not open-ended in any way. The rings are merely slipped over the ends of the bars and the rings and bars are brazed together at the points *3*.

Cast Squirrel-Cage Rotors

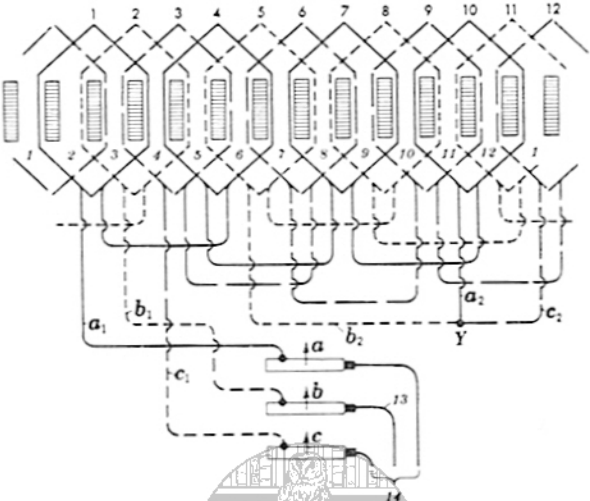
15. In rotors with end rings or the entire squirrel cage cast from special alloys, such as the rotor in Fig. 1*(b)*, look for cracked end rings or faulty joints between rings and bars. A faulty die-cast rotor can rarely be effectively repaired and should be replaced by a new one.

Electrical Faults in Lap-Wound Rotors

Three-Phase Lap-Wound Rotor

16. Rotor windings are very similar to stator windings. They are arranged in three phases, either star or delta, for two-phase and three-phase stators.

A three-phase rotor winding is balanced and symmetrical in every way. It is more convenient and better in several ways than a two-phase rotor, especially since its windings can be connected either star or delta. In some respects, it is cheaper



1 to *12*. slots
13. brushes
14. brush leads
a, b, c. collector rings
a_1, a_2, b_1, b_2, c_1, c_2. leads of phase windings
Y. star point
1 to 12. coils

FIG. 5. LAP-WOUND ROTOR WINDING

to build a three-phase rotor than a two-phase rotor. Without doubt, the torque of a three-phase rotor is more uniform in the various positions of the rotor than the torque of a two-phase rotor. A single-phase rotor is not used, because it will not start without some special starting device since its torque is only pulsating and not rotating.

A diagram of a typical lap winding in a three-phase rotor is shown in Fig. 5. This rotor has twelve slots, *1* to *12*, and twelve coils, 1 to 12, and each slot carries two coil halves. The three phase windings are connected in star. Leads a_1, b_1, and c_1 of one end of the three phase windings are connected to the corresponding collector rings a, b, and c, and the other three phase leads a_2, b_2, and c_2 are connected together to the

star point *Y*. The phase connected to the ring *a*, or phase *A*, contains coils 1, 4, 7, and 10 and leads a_1 and a_2; phase *B*, connected to ring *b*, contains coils 5, 8, 11, and 2 and leads b_1 and b_2; and phase *C*, connected to the ring *c*, contains coils 3, 6, 9, and 12 and leads c_1 and c_2. The coil pitch is three slots.

Starting Resistance

17. The collector rings *a*, *b*, and *c* in Fig. 5 are in contact with three brushes *13*. The brush leads *14* are connected to an adjustable resistance. This resistance is used with a phase-wound rotor for starting and – if designed for the service – may also be used for speed regulation.

The starting resistance closes the rotor circuit. In one type of motor, when the rotor has come up to speed the brushes are lifted from the rings, and the rings, and therefore the windings connected to them, are short-circuited; this is the normal running condition. The necessary operations may be either automatic or manual. In another method, the brushes remain on the rings and the brush leads go to a starting rheostat. In starting, the resistance of the starting rheostat is gradually cut out until contacts on the starter short-circuit the brush leads, thereby shorting also the outer ends of the three phase windings of the rotor.

Fault Tests

18. The coils of every definite phase winding, whether on a rotor or a stator, are insulated from the core slots and from one another. Hence, the phase windings of the rotor of an induction motor are subject to the same electrical faults as the stator windings of any a-c motor. If the windings have not been damaged badly, the regular tests for faults should be made. Before making any test, remove the brushes that bear on the collector rings, or put sheet insulation under them. Tag such insulation with a piece of paper that is large and brightly colored, so that you won't forget to take it out.

The tests for grounds, for open circuits, for short circuits, and for reversed coils may now be performed.

Test for Grounds

19. To test for grounds in a wound rotor, use the setup shown in Fig. 6(*a*). The test circuit is connected to a d-c or a-c source *1* and contains a test box, Megger, or lamp *2* and two test leads *3* and *4*. The test leads are placed across the shaft *5* and one of the three collector rings, *a*, *b*, or *c*. Here the lead *4* is shown on the collector ring *a*. All rings and coils should be insulated from the shaft, and the test should indicate high resistance to ground. If a test lamp is used, it will not light unless there is a ground. A low reading on the Megger or a lamp lighting shows a ground. If the test indicates a ground, try smoking out its location by holding the leads on for a time. If this does not work, cut the star point of the windings to separate the phases. With one test lead still on the shaft, apply the other to each ring in turn. The winding that shows a low resistance should be marked for repair.

Test for Open Star-Connected Circuits

20. Both star and delta connections are likely to have open circuits where the phase leads are connected to the collector rings. Tapping the leads with the hand or trying to pull them away from the ring will usually show up such a break.

The setup of Fig. 6(*b*) indicates the test procedure for finding an open circuit in a star-connected rotor winding. The windings are omitted from the illustration for simplicity. The six leads a_1, a_2, b_1, b_2, c_1, and c_2 and the star point Y are shown. With a lamp *2* in the circuit, put voltage from the source across the star point Y and each collector ring in turn. At the star point, use a test point *4* sharp enough to pierce the insulation. If the lamp does not light when the lead *3* is on a ring, either the phase winding connected to that ring is open or one of the leads is disconnected.

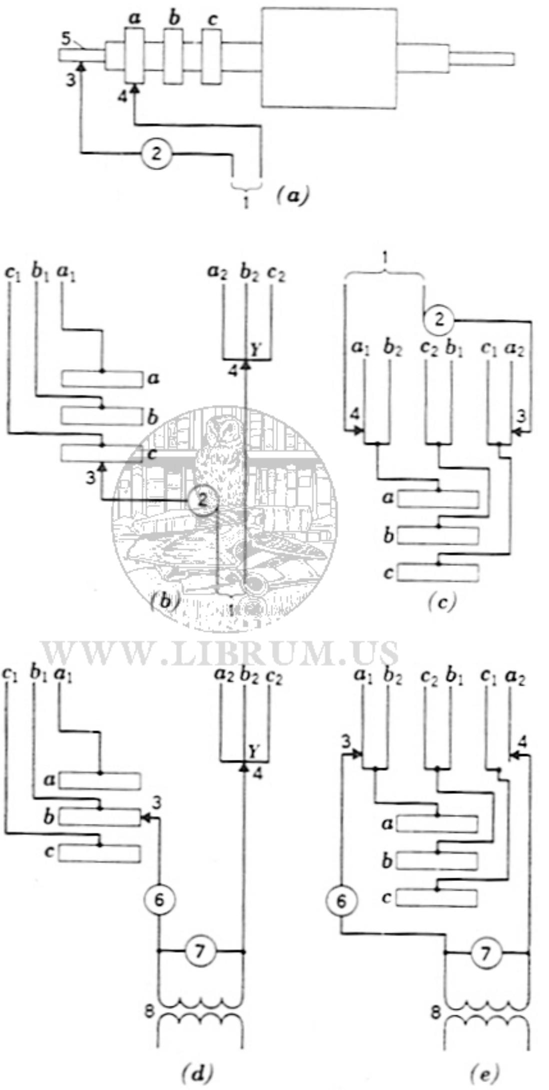


FIG. 6. SETUPS FOR TESTS ON LAP-WOUND ROTOR

Legend for Fig. 6

1. test-supply source
2. test box, Megger, or lamp
3, 4. test leads
5. shaft
6. ammeter
7. voltmeter
8. transformer
a, b, c. collector rings
$a_1, a_2, b_1, b_2, c_1, c_2$. phase-winding leads
Y. star point

(a) Test for ground
(b) Test for open circuit in star connection
(c) Test for open circuit in delta connection
(d) Balance test for short circuit in star connection
(e) Balance test for short circuit in delta connection

After you learn which phase is open, divide the winding in half to locate the exact fault point. The test leads should pierce the insulation, which will make cutting of the connections unnecessary. Then, find the good half. This positive indication is necessary mainly to make sure that both test points get clear through the insulation. Next, drop the good part, continuing work on the bad one. Divide it in half in the same way as before. Continue this elimination procedure until the fault point is located.

Test for Open Delta-Connected Circuits

21. If rotor winding is delta connected, as in Fig. 6*(c)*, first trace out the winding, identifying the leads and marking them so that each of the six leads is known. Then cut the connections between phases so as to isolate each phase. In the illustration, the actual cuts are not shown; they are outside the test leads. The test lead *3* is shown piercing the insulation of phase lead a_2, and the test lead *4*, piercing the phase lead a_1. This setup, with the phase leads cut properly, puts the test leads across the phase winding *A*.

Try all the phases the same way. When a phase is found to be open, the elimination method will locate the exact fault point. More than one break in the same phase is possible, even though it is not usual.

Growler Test for Short Circuits

22. To test for a short circuit in a part of a coil, or in an entire coil, use the same growler method used for locating defects in the stator winding or in the grid of a squirrel-cage rotor. Move the growler slowly over the rotor coils, watching the ammeter. When the ammeter reads high, the coil under the growler is shorted. A shorted coil becomes hot under the current induced in it by the growler, and may often be located by touch. If a whole coil is shorted, some wire outside the coil is at fault. To find this wire, go over the winding carefully, prying apart every pair of wires that cross and examining them. Sometimes a loose particle may cause at least a temporary short circuit when the rotor is up to speed and not at standstill.

Balance Test for Short Circuits

23. If a whole pole-phase group of coils is short-circuited, the balance test will determine the short circuit. The setup for a balance test of a star-connected rotor is shown in Fig. 6(*d*). The test circuit with the test leads *3* and *4* contains an ammeter *6* and a voltmeter *7*, and reduced line voltage is provided by a transformer *8*. Full line voltage, which would be correct for a stator balance test, would burn the rotor.

Test lead *4* is pushed into the star point; lead *3* goes to ring *b*. With lead *4* at the star point and the voltage constant, put lead *3* on the other rings in turn, reading the current for each phase. For correct operation of the motor, all phases should have the same current, although exact values are not so necessary as they are with the stator. A high current means a short circuit. The exact location of the short should then be found and the winding repaired.

A corresponding setup for the delta-connected winding is shown in Fig. 6(*e*). The phase windings are first separated where two leads meet, such as at the connection between c_2 and a_1, and then the test leads are applied to a_2 and a_1, across

the phase *A*. The test is made similarly for the other two phases. Currents in all phases should be equal. If they are not, find and repair the part or parts of the winding responsible for the short or shorts.

Compass Test for Coil Reversal

24. The compass test will locate a reversed coil for a phase-wound rotor in exactly the same way as for a three-phase stator. Send through each phase, in turn, a direct current that is about 5 percent of the normal full-load alternating current of the rotor. Run a compass slowly around the periphery of the rotor surface. Every time the compass needle draws parallel to the rotor shaft, mark an arrow on the rotor laminations, pointing in the same direction as the needle. If three arrows in succession point in the same direction, the middle arrow and its coil are reversed. To correct the fault, it is necessary only to interchange the leads of the reversed coil, which is easily done.

Test for Reversed Coil Group

25. Reversed coil groups occur in rotor windings as well as in stator windings. Either the balance test or the compass test will detect them. Like a shorted coil, a reversed coil group permits a higher current through its phase. After finding the phase with the reversed coil group, trace out the winding to find the reversed leads and correct them.

The reversal of an entire phase comes about for the phase-wound rotor in the same way as for the stator. The reversal of a phase is caused by an interchange of phase leads. This makes the direction of the current through one phase always the opposite of what it should be. To correct the trouble, reverse the faulty leads.

Wrong Number of Coils in Phase

26. The wrong number of coils in a rotor phase occurs just as it does in a stator winding. When one phase has a coil or more

too many, another phase has too few coils. The extra coils give the one phase winding too high an impedance, taking the extra amount from the other phase winding. Hence, the balance test will show too low a current in the one winding and too high a value in the other. After finding the high phase, trace out the winding with the help of a winding diagram until you find the wrong coil connection. Remember that coils connected wrongly may not all be in the same part of the rotor winding.

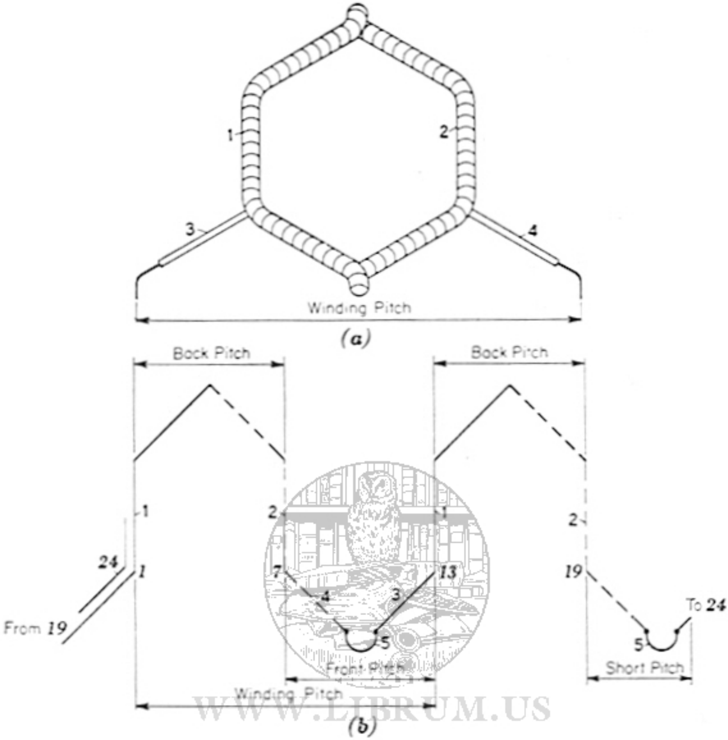
If a coil in any phase is not connected into the circuit, the effect on that phase will be the same as if the coil had been connected into a wrong phase. In a delicate balance test, the phase with coils omitted will have too high a current. However, if that phase has a large number of coils and only one is not connected, an ordinary balance test will not detect the difference in current between the phases. Such a situation requires a check of the coil connections and a count of the coils. The omitted coil, when found, should be connected in its circuit.

Characteristics of Wave Windings

Pitch Values of A-C Wave Windings

Importance of Wave Windings

27. Many electrical defects are substantially the same whether the windings are a-c or d-c, lap or wave. In addition, however, there are some faults peculiar to a-c wave windings. Determining the causes of these faults requires a good working knowledge of the fundamental principles of this winding. Many defects that the repairman is called upon to correct come from wrong changes in the connections made by someone not familiar with wave windings. When a certain hoist motor would not pull its rated load after repair, for example, examination showed that the phases had been connected



1. top coil side
2. bottom coil side
3. top lead
4. bottom lead
5. clip
1, 7, 13, 19, 24. slots

(*a*) Wave coil
(*b*) Wave-coil pitches measured in slots

FIG. 7. PITCHES FOR A-C WAVE WINDING

together internally, thus shorting out the external starting resistance.

Since the wave winding has many advantages over the lap winding, it is used increasingly in a-c induction motors. The principles of a-c wave windings are, however, both unique and complicated; they are also highly important to the repairman.

Therefore, these windings are discussed here in detail. First, the motor repairman should become familiar with the characteristics of a-c wave windings and with the most practical methods of preparing connecting and working diagrams by using connecting and checking tables.

Coils for Wave Windings

28. Wave windings on a-c rotors consist of coils similar to the coils in d-c wave windings. The coils are U shaped at the back of the core but have open ends at the front, like the one shown in Fig. 7*(a)*. Like most wave-winding coils, the coil shown is left-hand wound so that the left coil side *1* is the top half of the coil and the right coil side *2*, the bottom half. The top coil lead *3* and the bottom coil lead *4* are bent outward, or away from the coil sides. These leads are then connected to leads of other coils in the core to make a series of coils around the core. When the rotor is fully wound, the windings look like waves of leads, therefore the name "wave winding."

Back Pitch

29. In wave windings on a d-c machine one must distinguish between the coil-lead pitch and the commutator-bar pitch. The coil-lead pitch is the number of slots between the sides of one coil. It is determined by dividing the total number of slots by the number of poles. The commutator-bar pitch is the number of commutator bars between the leads of one coil.

In wave windings on a-c machines, the coil pitch has a somewhat different meaning.

Each coil of an a-c wave winding is almost always all in one piece in the back of the armature and the sides span a number of slots. The distance is set mechanically by the shape of the coil. The distance spanned by the coil in the back of the armature is the back pitch of the a-c wave winding, and is found by dividing the total number of slots by the number of poles. In this respect it is the same as the coil-lead pitch on

d-c machines. In Fig. 7*(b)* are represented two coils of a 24-slot rotor of a 4-pole motor. The full lines *1* indicate the top sides of the coils, and the broken lines *2*, their bottom sides. This method of representation will be used in all diagrams in this text. The first coil occupies slots 1 and 7 and the second coil occupies slots 13 and 19. The slots are not shown but only indicated by a numeral. Only slots occupied by the two coils are indicated. The back pitch of each coil is $\frac{24 \text{ slots}}{4 \text{ poles}} = 6$ slots, or from slot 1 to slot 7 and from slot 13 to slot 19.

In a wave winding, the back pitch is the same for all coils.

Front Pitch

30. Since the a-c wave winding does not use a commutator as does the d-c winding, the front ends of the coils must be connected together to form the basic series of coils. The number of coils in series connection in such a series is equal to half the number of poles. Each series of this kind goes around the core once. Several such series, or groups, make up the total phase winding.

In the winding shown in Fig. 7*(b)*, the bottom lead *4* of the first coil emerges from slot 7, bending away from the coil center and reaching three slots, or one-half the back pitch, to the right. The top lead *3* of the second coil emerges from slot 13, bending away from the coil center and reaching three slots to the left. The two leads from slots 7 and 13 are located very close and are connected together by a clip, or connector, *5*, which places the two coils in series. The span between the bottom coil side in slot 7 and the top coil side in slot 7 is called the front pitch of the wave winding. In this winding the front pitch is 6 slots, or the same as the back pitch.

Winding Pitch

31. The back pitch and the front pitch of a coil, both expressed in slots, must be added in order to pick up the slot needed for the next coil in the coil group.

The sum of the back pitch and the front pitch, expressed in slots, is called the winding pitch. In Fig. 7*(b)*, the winding pitch of the first coil is $6 + 6 = 12$ slots.

When the winding pitch is expressed in slots, it is equal to the total number of slots on the core divided by the number of pairs of poles, or one-half the number of poles. For example, for the rotor in Fig. 7*(b)*, with 2 pairs of poles the winding pitch is equal to $\frac{24}{2} = 12$ slots. It is the distance, in rotor slots, between any two stator poles of the same polarity. When the winding pitch is an even number, the back and front pitches are the same. In Fig. 7*(b)*, for example, the winding pitch is 12, and the back pitch and the front pitch are each 6 slots. When the winding pitch is an odd number, the back pitch has one slot more than the front pitch. If, for example, the winding pitch is 17 slots, the back pitch is 9 slots and the front pitch is 8 slots.

The winding pitch may also be determined as the distance between the end of the two leads of one coil, as indicated in Fig. 7*(a)*. The distance, in slots, is the same as the distance, in slots, obtained as the sum of the back and front pitches.

Short Pitch

32. As already mentioned, in a-c wave windings a series of coils encircles the rotor core. The number of coils in such a series is equal to one-half the number of poles. At the end of such a series, the front pitch must be shortened one slot in order to keep the series from closing on itself, regardless of whether the winding pitch is odd or even. For example, in Fig. 7*(b)*, the series of two coils encircles the core. If the front pitch of the second coil were six slots, like the full front pitch of the first coil, the next series of coils would again start in slot 1 and close the circuit around the rotor. To continue the series instead of closing it, one slot must be dropped from the front pitch. The pitch between the bottom lead from slot 19

and the top lead from slot 24 is therefore only five slots, or a short pitch. The common abbreviation for the short pitch is *SP*. A short pitch always comes at the end of a series of coils and the series ends one slot short of the starting point. This makes the wave windings retrogressive. All a-c wave windings are retrogressive.

In order to have a proper connection of coil leads at a short front pitch, the span of the top lead and that of the bottom lead of the coils to be connected must each be shortened one-half slot. When the coil conductors are light, the repairman can shape the leads as he goes along. Heavy conductors, however, must have special coils with shorter leads. Some of these coils will have short top leads, others will have short bottom leads; they will be placed in the proper slots to form a short pitch where required.

Slots per Pole per Phase, or SPP

33. The diagrams used in the motor industry to show coil-lead locations, coils pitch, collector-ring connections, coil grouping, short-pitch grouping, and similar matters for a-c rotor windings of the wave type have been more complicated and difficult to trace out than diagrams of lap windings. A simple and practical method of preparing and interpreting connection diagrams for wave windings will be used in this text. This method has been built up around the value of slots per pole per phase for each wave winding. The term "slots per pole per phase" is of primary importance in the connection of wave windings. The common abbreviation used for this term is *SPP*.

If the total number of slots on a rotor, or a stator, is divided by three times the number of poles, the quotient will give the SPP for the wave winding. For example, the SPP of a 120-slot rotor of a 10-pole motor is $\frac{120}{3 \times 10} = 4$ slots, or 4 SPP.

In usual commercial practice, the SPP values vary by half

TABLE 1

TOTAL NUMBER OF SLOTS FOR THREE-PHASE WAVE WINDINGS WITH VARIOUS NUMBERS OF POLES

SPP	2	2½	3	3½	4	4½	5	5½	6	6½	7	7½	8
Connection Diagram, Fig.	11		12	13	14		15		16				
Connection Table	3		5	7	9		11						
Checking Table	4		6	8	10		12						
Number of poles	Total Number of Slots												
4	24	30	36	42	48	54	60	66	72	78	84	90	96
6	36	45	54	63	72	81	90	99	108	117	126	135	144
8	48	60	72	84	96	108	120	132	144	156	168	180	192
10	60	75	90	105	120	135	150	165	180	195	210	225	240
12	72	90	108	126	144	162	180	198	216	234	252	270	288
14	84	105	126	147	168	189	210	231	252	273	294	315	336
16	96	120	144	168	192	216	240	264	288	312	336	360	384
18	108	135	162	189	216	243	270	297	324	351	378	405	432
20	120	150	180	210	240	270	300	330	360	390	420	450	480
22	132	165	198	231	264	297	330	363	396	429	462	495	528
24	144	180	216	252	288	324	360	396	432	468	504	540	576

slots, from 2 to 8, such as 2 SPP, $2\frac{1}{2}$ SPP, 3 SPP, on up to 8 SPP. The integral SPP values are 2, 3, 4, 5, 6, 7, and 8, and the fractional SPP values are $2\frac{1}{2}$, $3\frac{1}{2}$, $4\frac{1}{2}$, $5\frac{1}{2}$, $6\frac{1}{2}$, and $7\frac{1}{2}$. The term "slots per pole per phase" is used in stator as well as in rotor windings if they are wave wound.

For all windings with the same SPP value, regardless of the number of poles and slots, the winding pitch and the short pitch are the same. This fact should be kept in mind throughout the following discussions.

Total Number of Slots Determined by SPP

34. There is a direct way to find the total number of rotor slots if the SPP and the number of poles are known. Since the rotors are assumed to have three phase windings, *multiply SPP by three times the number of poles to determine the total number of slots*. For example, in the 10-pole 4-SPP motor, the total number of slots is $4 \times 3 \times 10 = 120$ slots. This is just one of many ways in which the SPP value is helpful in the study of wave windings.

For each value of SPP, there are several possible combinations of stator poles and total number of rotor slots. For example, 2 SPP can be obtained with 24 slots and 4 poles, or with 36 slots and 6 poles, to name a few of the many combinations. The total number of slots in three-phase a-c wave windings with various numbers of poles is given in Table 1 for commercial values of SPP from two to eight, in steps of one-half slot per pole, and for 4 to 24 poles, in steps of two poles. This table applies only to three-phase wave-wound rotors. Table 1 is a highly important summary, a master table. To a person who knows how to use it, this table tells far more than just what the headings and figures present. For this reason, it is more than a reference table, and is worth considerable study.

Connection diagrams for some of the windings listed in Table 1 are given in this text. The numbers of the illustrations in which these diagrams appear are given in the table, as well

as the numbers of connection tables and checking tables used to prepare the diagrams.

When possible changes in the number of poles are considered, for the purpose of changing speed or frequency, Table 1 may be helpful. For example, the table shows that 96 slots can be used for a 16-pole winding with 2 SPP, for an 8-pole winding with 4 SPP, and for a 4-pole 8-SPP winding. Similarly, 120 slots can be used for a 20-pole 2-SPP winding, a 16-pole $2\frac{1}{2}$-SPP winding, a 10-pole 4-SPP winding, and an 8-pole 5-SPP winding.

If the total number of slots of a rotor divided by three times the number of poles does not give one of the listed values of SPP, the rotor is not suitable for wave windings. For example, a 200-slot rotor is not suitable for a 20-pole motor because the $\text{SPP} = \frac{200}{3 \times 20} = 3\frac{1}{3}$ slots, which is neither 3 nor $3\frac{1}{2}$. According to Table 1, 200 slots are not suitable for any usual combination of poles and SPP for three-phase wave windings.

Winding Pitch Determined by SPP

35. As was mentioned before, the winding pitch is determined by dividing the total number of slots by half the number of poles. Apply this rule to the rotors with various numbers of slots for various numbers of poles listed for the value 2 SPP in Table 1. For example, for a 24-slot 4-pole combination, the winding pitch is $\frac{24}{2} = 12$ slots; for a 36-slot 6-pole combination, it is $\frac{36}{3} = 12$ slots; for a 48-slot 8-pole combination, it is $\frac{48}{4} = 12$ slots. It is easily seen that all rotors with the value 2 SPP have the same winding pitch of 12 slots, regardless of the number of poles. For the value $2\frac{1}{2}$ SPP, the same fact may be proved: $\frac{30 \text{ slots}}{2 \text{ poles}} = 15$ slots, $\frac{45 \text{ slots}}{3 \text{ poles}} = 15$ slots, and so on.

It can also be seen that the winding pitch is always six times greater than the SPP. Thus, we have the rule: *Multiply SPP by six to determine the winding pitch.*

Since the winding pitch is the same for all windings with the same SPP, a single connection diagram can be made to cover all the combinations of slots and poles that result in the same number of slots per pole per phase.

If the winding has an integral SPP value, the winding pitch always has an even number of slots, and the back and the front pitch have the same number of slots. If, however, the winding has a fractional SPP value, the winding pitch always has an odd number of slots, and the back pitch has one slot more than the front pitch. For example, a 3-SPP winding has a winding pitch of $6 \times 3 = 18$ slots, and the back pitch is 9 slots and the front pitch is 9 slots. In a winding with $3\frac{1}{2}$ SPP, the winding pitch is $6 \times 3\frac{1}{2} = 21$ slots, and the back pitch is 11 slots and the front pitch is one slot shorter, or 10 slots.

The short pitch is always one slot shorter than the front pitch, regardless of the number of poles.

The fact that the winding pitch for a rotor with a selected SPP value does not depend on the number of poles is one of the main characteristics of a-c wave windings. The same back pitch and the same short pitch mean that the same coils may be used and the same pattern of winding. The number of poles may be changed simply by reconnecting the same coils in their original slots.

Phase Leads

Sections of Wave Windings

36. Another characteristic of a-c wave windings is that the windings are divided into six sections which form separate circuits. Since the windings consist of three phases, each phase is divided into two sections, each of which consists of several coils connected in series.

For correct connection of wave windings, first, individual coils must be connected in series to form a closed circuit in each section, and second, the six sections must be properly connected to the collector rings or to the line. The way the sections are selected depends on the most convenient location of their end leads.

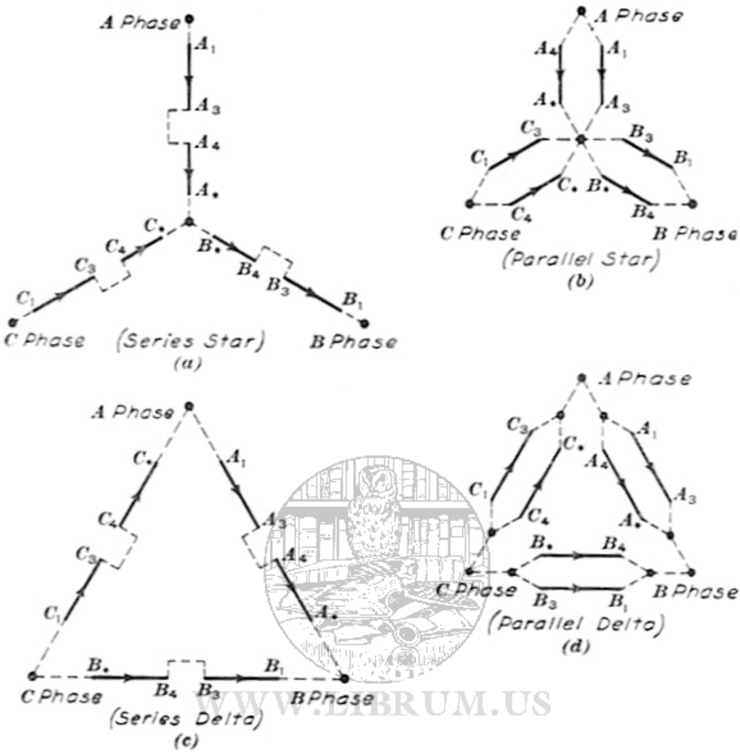
To avoid errors, standard symbols are used for the end leads of these six sections. There are 12 free phase leads in each winding. The three phases are A, B, and C. The free lead at the beginning of the first section of phase A is A_1, or lead No. 1, the line lead, which is always a bottom lead. The free lead at the end of the first section of phase A is A_3, or lead No. 3, which is always a top lead. The free lead at the beginning of the second section of phase A is A_4, or lead No. 4, which is always a top lead; and the end lead is A_*, or star lead, which is always a bottom lead.

Similarly, in the remaining phases B and C, there are leads B_1, C_1, B_3, C_3, B_4, C_4, B_*, and C_*.

Clips and Crossconnectors

37. The six sections of the three phases of a wave winding consist of coils connected in series. Each coil occupies two slots, but each slot contains one bottom side and one top side of a coil or two conductors. Thus, there are as many coils as there are slots in the winding. For a selected value of SPP and total number of slots, the pitch of the coils is fixed. When all coils have been placed in the slots, each slot contains a bottom and a top side of a coil and there are two rows of leads around the core, the bottom leads and the top leads.

These leads are joined by clips, or connectors, so that the coils are connected in series in each of the six sections. It is a practical feature of the wave winding that a bottom lead and a top lead which are adjacent can be joined in the clip placing their two coils in series. This can be done with all leads between coils except the twelve free leads of coil sections. The



Type of Connection	Diagram	Lead Connected to Line or Slip Ring			Reversing Jumpers	Star-Point Connections
		A Phase	B Phase	C Phase		
Series star	(a)	A_1	B_1	C_1	A_3 to A_4 B_3 to B_4 C_3 to C_4	A_2, B_2, C_2
Parallel star	(b)	A_1, A_4	B_1, B_4	C_1, C_4	None	A_2, B_2, C_2 A_3, B_3, C_3
Series delta	(c)	A_1, C_2	B_1, A_2	C_1, B_2	A_3 to A_4 B_3 to B_4 C_3 to C_4	None
Parallel delta	(d)	A_1, A_4 C_3, C_2	B_1, B_4 A_3, A_2	C_1, C_4 B_3, B_2	None	None

FIG. 8. CONNECTIONS OF PHASE LEADS

use of clips on adjacent leads reduces the use of cross connectors, or reversing jumpers, to a minimum. Cross connectors are necessary only to connect leads No. 3 and No. 4 of two sections if the two sections should be connected in series.

The reduction in the number of cross connectors makes the wave winding much more desirable than the lap winding, and is the main reason why wave windings are preferable.

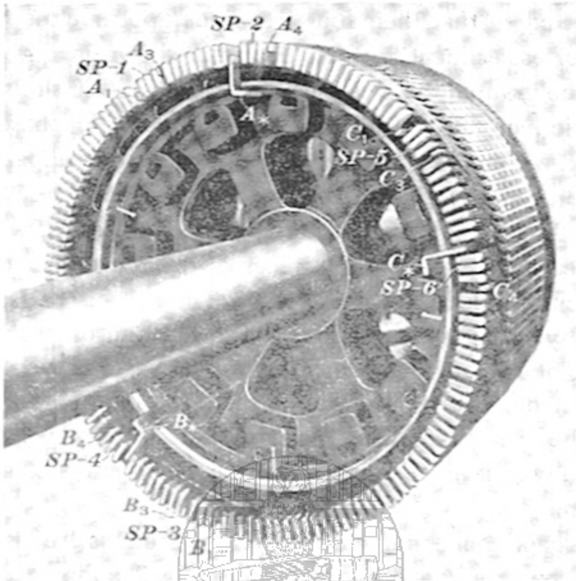
Star and Delta Connections

38. With the twelve leads of an a-c wave winding, four different connections can be made: series star, parallel star, series delta, and parallel delta.

The tabular part of Fig. 8 indicates the arrangement of phase leads for the four connections. The sixth column shows which phase leads are to be connected together by the reversing jumper that joins the two sections of each phase in a series connection.

The diagrams *(a)*, *(b)*, *(c)*, and *(d)* in Fig. 8 form a guide for the connections of the six sections in the four possible types of connections indicated in the table in Fig. 8. Leads A_1, B_1, and C_1 are considered the line leads because they are connected to the line or to the slip rings. Leads $A_\bullet$, $B_\bullet$, and $C_\bullet$ are the star leads, which are connected directly to the common star point in series-star and parallel-star connections. Leads No. 3 and No. 4 within a phase are connected together by reversing jumpers, or cross connectors, in series-star and series-delta connections, as indicated by broken lines in *(a)* and *(c)*. In parallel-star and parallel-delta connections, leads No. 3 and No. 4 are connected as shown in *(b)* and *(d)*. There are no reversing jumpers in parallel-star or parallel-delta connections.

All three-phase wave windings have six sections. This fact can be used to detect unwanted connections, or interconnections, as follows: Consider the winding to have all clips in place and to have unconnected only the 12 phase leads, that is,



A_1, $A_\bullet$, B_1, $B_\bullet$, C_1, $C_\bullet$, bottom leads
A_3, A_4, B_3, B_4, C_3, C_4, top leads
SP-1 to SP-6, short pitches

FIG. 9. WAVE-WOUND ROTOR

the three line leads, the three star leads, and the six reversing-jumper leads. To see whether the clips on the other coils have been placed correctly, hold a lead from a test lamp on lead A_1, touching all the other leads in turn. Only leads A_1 and A_3 should show a complete path for the current. Similar testing of the other leads should show connection only between the following pairs: B_1 and B_3, C_1 and C_3, A_4 and $A_\bullet$, B_4 and $B_\bullet$, and C_4 and $C_\bullet$. None of the other pairs of leads should have a completed path for current between them, because they do not belong to the same sections.

Grouping of Free Phase Leads

39. Another important feature of wave winding is the location of the phase leads. The two sections of one phase can

be selected so that their four free ends appear close to each other for easier identification. The rotor shown in Fig. 9 illustrates the grouping of free phase leads. It is a 120-slot rotor of a 10-pole motor. The leads A_1, A_3, A_4, and $A_{\bullet}$ for phase A are grouped within a short distance, as shown at the upper left of the rotor. Similar groups of leads are visible for phases B and C. The three groups are spaced 120 deg (degrees) apart.

When a motor repairman receives the rotor, he must first locate and mark the 12 phase leads. The rest of the leads are then easy to check or reconnect. The location of phase leads and the number of clips between them indicate the location of short pitches (SP) and the determination of the SPP value. Once the SPP value of the rotor has been determined, the repairman will have enough information to prepare a connection diagram.

The clips connecting coils within the sections are visible all around the periphery of the rotor in Fig. 9. The three star leads $A_{\bullet}$, $B_{\bullet}$, and $C_{\bullet}$ are the easiest leads to identify because they are connected to the common star point and are bottom leads. Once the lead $A_{\bullet}$ is found, the repairman looks for leads without clips within a short distance of $A_{\bullet}$. As seen in Fig. 9, there is one bottom lead and two top leads without clips close to $A_{\bullet}$. The bottom lead must be the line lead, or A_1, because the No. 1 lead is always a bottom lead. The two top leads are A_3 and A_4. The leads of phases B and C are similarly identified.

Determining SP

40. In Fig. 9 three clips are visible between A_1 and A_3, and between $A_{\bullet}$ and A_4. These clips indicate the SP connections in the windings. There are two places in each phase where the SP connections are grouped, as will be seen in the winding diagram. The groups of SP connections are designated by *SP-1* and *SP-2* for phase *A*, *SP-3* and *SP-4* for phase *B*, and *SP-5* and *SP-6* for phase *C*. The number of clips in each SP group indicates the number of SP connections, but it does not indicate the number of slots in the short pitch.

The number of clips in the SP connections is important to the repairman because it gives an indication of the SPP value for this rotor.

Determining Slots per Pole per Phase

Determining SPP from SP

41. Examination of any fully connected a-c wave winding will easily determine the number of slots per pole per phase. First locate any group of phase leads; such leads are always grouped in two bottom leads and two top leads, as in Fig. 9. Each phase group starts at a single bottom lead and ends on a single top lead, with two leads in between. These two inner single leads are spaced from the leads at each end of the group by a number of clips equal to one less than the SPP.

For example, C_{*} is three clips from C_4, and C_3 is three clips from C_1. Hence, the number of slots per pole per phase for this winding is $3 + 1 = 4$ slots, or 4 SPP.

When there is an integral number of slots per pole per phase, the number of clips between leads No. 1 and No. 3, and between star lead and lead No. 4 in each phase, will be the same. Therefore, in wave windings with integral SPP, *the number of clips at any SP plus 1 equals SPP*. For example, in Fig. 9, all SP groups have three clips, and the SPP value is $3 + 1 = 4$ SPP.

For a fractional number of slots per pole per phase, such as $2\frac{1}{2}$ or $3\frac{1}{2}$, the number of clips at *SP-1* will be one more than the number at *SP-2*. To find the SPP, add together the numbers of clips at *SP-1* and *SP-2*; to the sum add two, and then divide this total by two. For example, if a rotor has 3 clips in group *SP-1* and 2 clips in *SP-2*, the SPP value is $\dfrac{3 + 2 + 2}{2} = 3\frac{1}{2}$ SPP. This method is perhaps the simplest way to find fractional values of SPP.

Of course, this same rule works also for an integral number

of SPP. In Fig. 9, for example, the SPP value can be found as $\frac{3+3+2}{2} = 4$ SPP, as has been found before by simply adding one to the SP clips.

A positive check on the number of slots per pole per phase, for any rotor winding, is the number of clips between any No. 3 lead and star lead of the phase, such as C_3 and C_*. *The number of clips between the No. 3 lead and the star lead is always equal to twice the value of SPP.* For example, in Fig. 9, there are 8 clips between C_3 and C_*, or $\frac{8}{2} = 4$ SPP.

Any three-phase wave winding can be classified in regard to SPP by examining the phase-lead groups and counting the clips between them. Once the SPP has been established, other characteristics, such as the number of poles or the number of slots in the winding pitch, back pitch, and short pitch, are easily determined, as explained earlier in this text.

More Than Two Conductors per Slot

42. The rules about counting the clips hold good for windings having two conductors, or coil sides, per slot. The winding in Fig. 9 has two straps in parallel in each coil side, but both straps are in one lead, and are therefore considered as one conductor. If, on some experimental machine, a multiconductor cable were used in the same way, its many strands would also be considered a single conductor.

Unless otherwise specified, windings with two conductors per slot are assumed in discussions in this text.

There are, however, many windings with four, six, or eight conductors per slot, which means two, three, or four conductors per coil. Windings with more than two electrically distinct conductors per slot have more clips than windings with two conductors per slot, in fact, as many times more as there are pairs of conductors per slot. So, when counting the clips in an SP group to find the SPP, the number obtained by applying the

regular rule must be divided by half the number of conductors per slot to obtain the SPP value.

Assume, for example, that in a rotor with six conductors per slot, the number of clips in *SP-5* is 8 and the number in *SP-6* is 5. Apply the rule of adding 8 + 5 + 2, and divide the sum by 2, or $\frac{8+5+2}{2} = \frac{15}{2}$. This value is *not* the SPP value, because there are six conductors per slot in this rotor. Divide $\frac{15}{2}$ by $\frac{6}{2}$ to obtain the SPP, or SPP $= \frac{15}{2} \div 3 = \frac{5}{2} = 2\frac{1}{2}$ slots, or $2\frac{1}{2}$ SPP.

A positive check may be made for the SPP value if the clips between lead No. 3 and the star lead in a phase are counted. Twice the number of clips is the SPP value if there are two conductors per slot. If, however, there are more than two conductors per slot, the result obtained by regular rule should be divided by half the number of conductors per slot.

In the previously mentioned example, there will be 15 clips between C_3 and C_*. The rule gives the value $\frac{15}{2}$, but this is *not* the SPP value. Divide it by $\frac{6}{2}$ to obtain the SPP, or SPP $= \frac{15}{2} \div 3 = \frac{5}{2} = 2\frac{1}{2}$ slots, or the same as obtained when counting clips in SP groups.

All these rules are highly important to the practical repairman; memorizing them will save time in the long run.

In order to eliminate calculations, Table 2 lists the actual number of clips at SP groups in windings with 2, 4, 6, and 8 conductors per slot for SPP values from 2 to 8. The two columns under the heading "Two Conductors per Slot" indicate the same number of slots as other diagrams and tables in the text. The other columns give the clips for 4, 6, or 8 conductors per slot. The correctness of the calculations may be checked against Table 2. For example, for the $2\frac{1}{2}$ SPP obtained in the example in this article, the table gives, in the column "Six Conductors

TABLE 2

NUMBER OF CLIPS AT THE SHORT-PITCH POINTS

Slots per Pole per Phase	Two Conductors per Slot		Four Conductors per Slot		Six Conductors per Slot		Eight Conductors per Slot	
	SP 1-3-5	*SP* 2-4-6	*SP* 1-3-5	*SP* 2-4-6	*SP* 1-3-5	*SP* 2-4-6	*SP* 1-3-5	*SP* 2-4-6
2	1	1	3	3	5	5	7	7
$2\frac{1}{2}$	2	1	5	3	8	5	11	7
3	2	2	5	5	8	8	11	11
$3\frac{1}{2}$	3	2	7	5	11	8	15	11
4	3	3	7	7	11	11	15	15
$4\frac{1}{2}$	4	3	9	7	14	11	19	15
5	4	4	9	9	14	14	19	19
$5\frac{1}{2}$	5	4	11	9	17	14	23	19
6	5	5	11	11	17	17	23	23
$6\frac{1}{2}$	6	5	13	11	20	17	27	23
7	6	6	13	13	20	20	27	27
$7\frac{1}{2}$	7	6	15	13	23	20	31	27
8	7	7	15	15	23	23	31	31

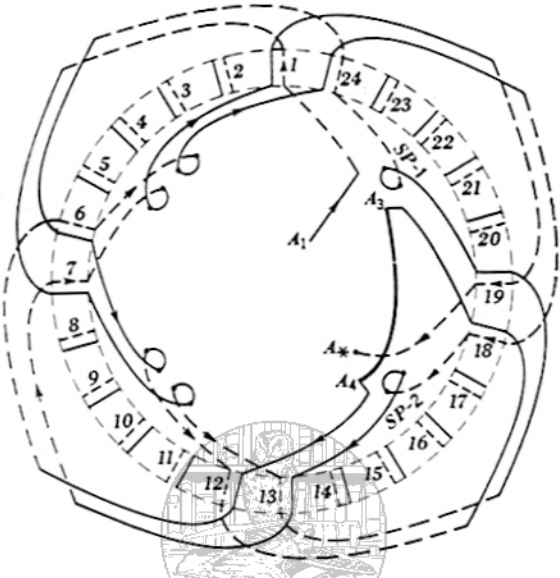
per Slot," 8 clips in the *SP*-5 group and 5 clips in the *SP*-6 group, as assumed in the example.

On the other hand, if the SPP value is known, and the number of clips in the SP groups should be determined, Table 2 is again very practical, because it gives the desired number directly and eliminates the calculations.

EXAMPLE 1. A rotor with 6 conductors per slot has 2 SPP. How many clips are in each SP group?

SOLUTION. Multiply the SPP by half the number of conductors per slot, or $2 \times \frac{6}{2} = 6$. Since the SPP is an even number, subtract 1 from the result, or $6 - 1 = 5$ clips. Ans.

Check: Table 2 gives the value 5 for 6 conductors per slot and 2 SPP.



1 to *24*. slots
A_1, A_2, A_3, A_4. phase leads
SP-1, *SP-2*. short-pitch groups

FIG. 10. COMPLETE DIAGRAM OF ONE PHASE ON WAVE-WOUND ROTOR

EXAMPLE 2. A rotor with 8 conductors per slot has $5\frac{1}{2}$ SPP. How many clips are in each SP group?

SOLUTION. Multiply the SPP by half the number of conductors per slot, or $5\frac{1}{2} \times \frac{8}{2} = \frac{88}{4} = 22$. Since the SPP is a fractional value, multiply the result by 2, and then subtract 2; thus, $(22 \times 2) - 2 = 42$. This is the total number of clips in *SP-1* and *SP-2* together. The difference in clips is equal to half the number of conductors per slot, or 4 clips. Find two numbers which, added together, give 42, with one four higher than the other. These numbers are 23 and 19. So, *SP-1-3-5* each have 23 clips and *SP-2-4-6* each have 19 clips. Ans.

Again, Table 2 gives these values directly for $5\frac{1}{2}$ SPP and 8 conductors per slot, eliminating all calculations.

Connection Diagrams and Tables

Complete Diagram

43. Before the simplified way of presenting connection diagrams for a-c wave windings is discussed, it will be beneficial to study a complete diagram of a wave winding. After studying the diagram of actual coil positions and connections shown in Fig. 10, the simplicity of the connection diagrams used in this text will be more fully understood and appreciated. The diagram in Fig. 10 shows a 24-slot rotor for a 4-pole motor. It is one of the simplest possible windings because it uses the lowest applicable number of slots and poles. And yet, it would be hard to follow if all the coils and connections were shown. Thus, only one phase is shown, fully wound, with all the coils, leads, and connections. The slots in Fig. 10 are marked by numbers *1* to *24* counterclockwise around the rotor. The coils are all left wound; that is, the left side (full line) is the top side of the coil and the right side (broken line) is the bottom side. Since there are 24 slots and 4 poles, the SPP $= \frac{24}{3 \times 4} = 2$. The back pitch of coils is $\frac{24}{4} = 6$ slots, the front pitch is 6 slots, and the short pitch is 5 slots. The arrows indicate the sequence of coils within a phase.

The bottom lead emerging from slot *1* is always selected as the line lead A_1. The first coil occupies the bottom of slot *1* and the top of slot *7*. The top lead from slot *7* extends away from its coil for 3 slots and ends very close to the bottom lead from slot *13*, which belongs to a coil in slots *13* and *19*, and also extends 3 slots away from slot *13*. The two adjacent leads from slots *7* and *13* are connected by a clip, and so their two coils are in series. The top lead from slot *19* should be shortened and connected to a shortened bottom lead from slot *24* to make a front pitch of only 5 slots, or a short pitch *SP-1*; otherwise the circuit would close itself through the two coils and would be connected to A_1. The two coils circle the rotor once, and now the second series around the rotor begins.

The coil with bottom side in slot *24* has its top side in slot *6*, and its lead is connected by a clip to the bottom lead from slot *12*. The top side of the coil with one side at the bottom of slot *12* is on top of slot *18*, and its lead A_3 is left free as the end of the first section of phase *A*. The first section consists of two series of coils around the rotor, each series having two coils.

The second section of phase *A* starts with the free lead A_4, which is the top lead emerging from slot *12*. The coil with the top side in slot *12* has its bottom side in slot *6*; the bottom lead from this coil is connected by a clip to the top lead from slot *24*. The coil with the top side in slot *24* has the bottom side in slot *18*, and its bottom lead is again shortened to make a short front pitch *SP-2*, because this is the end of the first series in the second section of phase *A*. A clip connects the bottom lead from slot *18* to the top lead from slot *13*. The coil with top side in slot *13* has its bottom side in slot *7*. The bottom lead is connected by a clip to the top lead from slot *1*. The coil with the top side in slot *1* has its bottom side in slot *19*. The bottom lead from slot *19* is the free star lead A_0. This lead ends the second section of phase *A*, which consists of two coil series, each with two coils.

Reversing Jumpers and SPP

44. In the winding shown in Fig. 10 all connections between coils have been made by clips which connect the adjacent leads. If the winding is to be series-star connected, as in Fig. 8(*a*), the leads A_3 and A_4 must be connected by a reversing jumper. The jumper is shown by a heavy line in Fig. 10. This is the only jumper for phase *A*, and the entire winding will need only three reversing jumpers. As mentioned before, reduction in the number of jumpers is one of the main advantages of the wave winding over the lap winding for a-c windings.

Assume that the rotor in Fig. 10 is fully wound with all coils in place and all clips and reversing jumpers connected. Try to determine the SPP and other data by counting clips according to the previously explained rules.

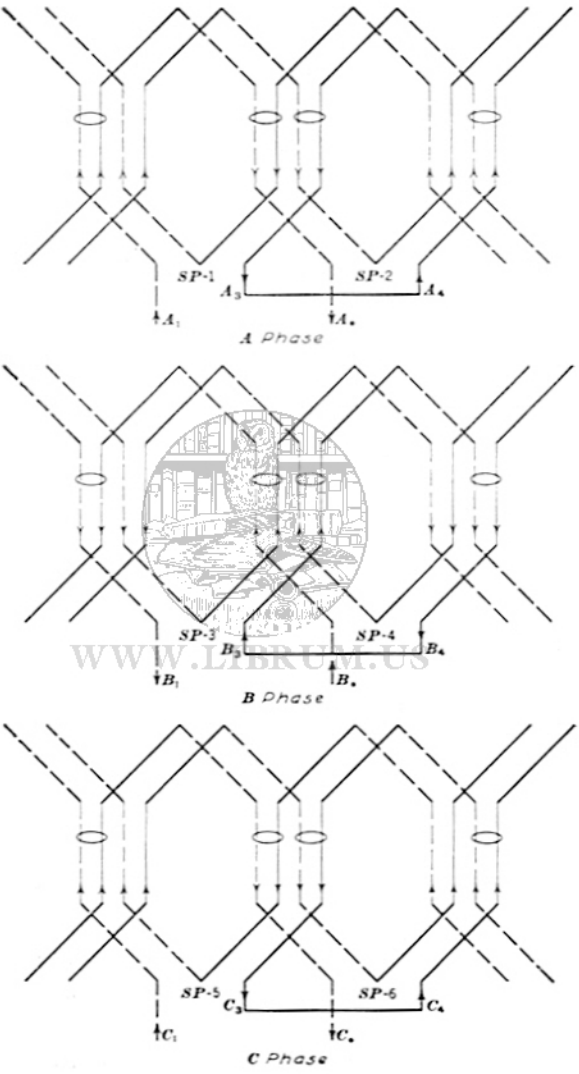


FIG. 11. CONNECTION DIAGRAM FOR 2-SPP WINDINGS

TABLE 3

CONNECTION TABLE FOR TWO SLOTS PER POLE PER PHASE

Number of Poles	Number of Slots	A Phase				B Phase				C Phase				Short Pitch Number of Clips	
		Bottom Leads		Top Leads		Bottom Leads		Top Leads		Bottom Leads		Top Leads			
		A_1	A_2	A_3	A_4	B_1	B_2	B_3	B_4	C_1	C_2	C_3	C_4	SP 1-3-5	SP 2-4-6
4	24	↑ 1	19	18	12	↓ 9	3	2	20	↑ 17	11	10	4	1	1
6	36	↑ 1	31	30	24	↓ 9	3	2	32	↑ 29	23	22	16	1	1
8	48	↑ 1	43	42	36	↓ 33	27	26	20	↑ 17	11	10	4	1	1
10	60	↑ 1	55	54	48	↓ 21	15	14	8	↑ 41	35	34	28	1	1
12	72	↑ 1	67	66	60	↓ 57	51	50	44	↑ 29	23	22	16	1	1
14	84	↑ 1	79	78	72	↓ 57	51	50	44	↑ 29	23	22	16	1	1
16	96	↑ 1	91	90	84	↓ 33	27	26	20	↑ 65	59	58	52	1	1
18	108	↑ 1	103	102	96	↓ 33	27	26	20	↑ 77	71	70	64	1	1
20	120	↑ 1	115	114	108	↓ 81	75	74	68	↑ 41	35	34	28	1	1
22	132	↑ 1	127	126	120	↓ 45	39	38	32	↑ 89	83	82	76	1	1
24	144	↑ 1	139	138	132	↓ 57	51	50	44	↑ 113	107	106	100	1	1

Back and front pitches = 6 slots. Short pitch = 5 slots.

TABLE 4

CHECKING TABLE FOR TWO SLOTS PER POLE PER PHASE

Number of Slots	Number of Poles	Polarity	*C* Phase		*B* Phase		*A* Phase	
24	4	↑	5	4	3	2	1	Z
		↓	11	10	9	8	7	6
		↑	17	16	15	14	13	12
		↓	23	22	21	20	19	18
36	6	↑	29	28	27	26	25	24
		↓	35	34	33	32	31	30
48	8	↑	41	40	39	38	37	36
		↓	47	46	45	44	43	42
60	10	↑	53	52	51	50	49	48
		↓	59	58	57	56	55	54
72	12	↑	65	64	63	62	61	60
		↓	71	70	69	68	67	66
84	14	↑	77	76	75	74	73	72
		↓	83	82	81	80	79	78
96	16	↑	89	88	87	86	85	84
		↓	95	94	93	92	91	90
108	18	↑	101	100	99	98	97	96
		↓	107	106	105	104	103	102
120	20	↑	113	112	111	110	109	108
		↓	119	118	117	116	115	114
132	22	↑	125	124	123	122	121	120
		↓	131	130	129	128	127	126
144	24	↑	137	136	135	134	133	132
		↓	143	142	141	140	139	138

First, it is seen that the four phase leads for phase *A* are grouped close together (the same would be true for all other phases). Between A_1 and A_3 and between A_2 and A_4 there is only one clip. Since the SP group always contains one less clip than SPP, the SPP value for this winding is 2 SPP. A positive check would be to count the clips between A_3 and A_2. In Fig.

10 there is room for four clips between these two leads. If all coils were wound in place, there would be four clips from phases B and C between A_3 and A_4. One-half of this number is the SPP, or $\frac{4}{2} = 2$ SPP. So, by double-checking the clips, it has been established that the winding in Fig. 10 is based on 2 SPP.

From the SPP value it can be determined that the winding pitch is $6 \times 2 = 12$ slots, which may be verified in Fig. 10. Since the winding pitch is an even number, the back pitch and the front pitch must each be 6 slots, which is also visible in Fig. 10. Each short pitch is $6 - 1 = 5$ slots.

Connection Diagrams

45. When the SPP value of a wave winding is known or selected, the connection diagrams may be simplified. The connection diagrams in Figs. 11 through 16 are samples of diagrams based on SPP values and are most practical for a-c wave windings. They are diagrams for SPP values of 2, 3, $3\frac{1}{2}$, 4, 5, and 6. These diagrams do not indicate the slots or slot numbers, because the same diagrams may be applied to any wave windings with the same SPP values, regardless of the number of slots and poles. Each diagram represents windings with the same winding pitch and the same short pitches. The positions of the four phase leads and SP groups are shown for each phase, indicating in a general way the pattern of winding. When the pattern is known, it is not necessary to have a complete diagram of all slots and coils like the one in Fig. 10.

A simplified connection diagram for the winding in Fig. 10 is shown in Fig. 11. This same diagram applies equally well to any winding with 2 SPP and any combination of slots and poles indicated in Table 1. The back and the front pitch is 6 slots and the short pitch is 5 slots.

A connection diagram should be prepared for each repair job. As shown in Fig. 11, the connection diagram actually consists of three diagrams, one for each of the phases, A, B, and C.

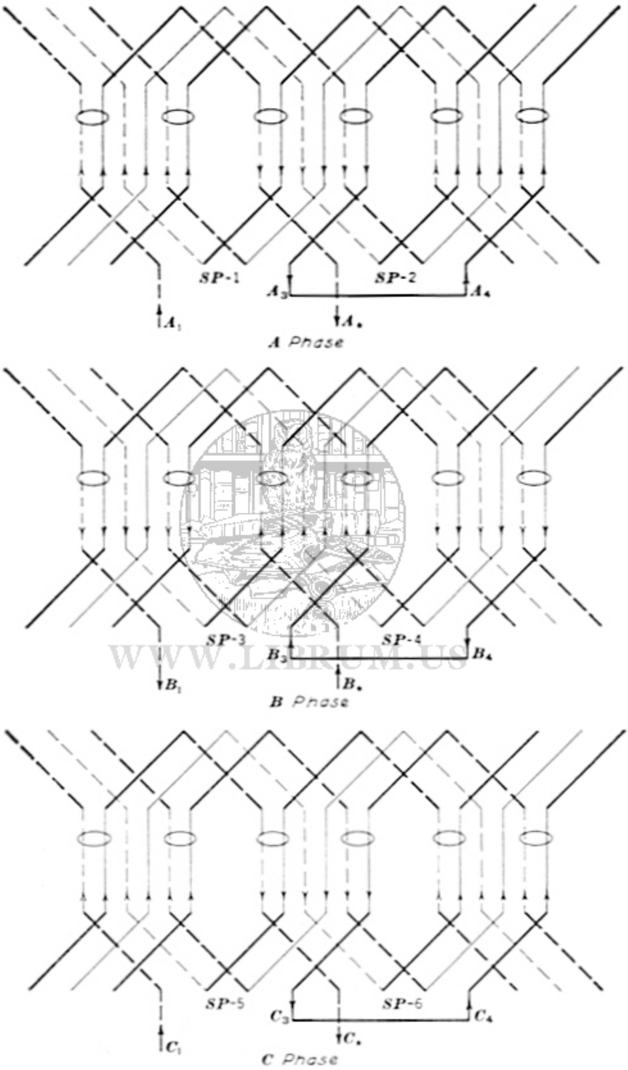


FIG. 12. CONNECTION DIAGRAM FOR 3-SPP-WINDINGS

TABLE 5

CONNECTION TABLE FOR THREE SLOTS PER POLE PER PHASE

Number of Poles	Number of Slots	A Phase				B Phase				C Phase				Short Pitch Number of Clips	
		Bottom Leads		Top Leads		Bottom Leads		Top Leads		Bottom Leads		Top Leads			
		A_1	A_2	A_3	A_4	B_1	B_2	B_3	B_4	C_1	C_2	C_3	C_4	*SP* 1-3-5	*SP* 2-4-6
4	36	↑ 1	28	26	17	↓ 13	4	2	29	↑ 25	16	14	5	2	2
6	54	↑ 1	46	44	35	↓ 13	4	2	47	↑ 25	16	14	5	2	2
8	72	↑ 1	64	62	53	↓ 49	40	38	29	↑ 25	16	14	5	2	2
10	90	↑ 1	82	80	71	↓ 31	22	20	11	↑ 61	52	50	41	2	2
12	108	↑ 1	100	98	89	↓ 31	22	20	11	↑ 61	52	50	41	2	2
14	126	↑ 1	118	116	107	↓ 85	76	74	65	↑ 43	34	32	23	2	2
16	144	↑ 1	136	134	125	↓ 49	40	38	29	↑ 97	88	86	77	2	2
18	162	↑ 1	154	152	143	↓ 67	58	56	47	↑ 115	106	104	95	2	2
20	180	↑ 1	172	170	161	↓ 121	112	110	101	↑ 61	52	50	41	2	2
22	198	↑ 1	190	188	179	↓ 67	58	56	47	↑ 133	124	122	113	2	2
24	216	↑ 1	208	206	197	↓ 139	130	128	119	↑ 61	52	50	41	2	2

Back and front pitches = 9 slots. Short pitch = 8 slots.

TABLE 6

CHECKING TABLE FOR THREE SLOTS PER POLE PER PHASE

Number of Slots	Number of Poles	Polarity	●	C Phase	●	●	B Phase	●	●	A Phase	●
36	4	↑	7	6	5	4	3	2	1	Z	Y
		↓	16	15	14	13	12	11	10	9	8
		↑	25	24	23	22	21	20	19	18	17
		↓	34	33	32	31	30	29	28	27	26
54	6	↑	43	42	41	40	39	38	37	36	35
		↓	52	51	50	49	48	47	46	45	44
72	8	↑	61	60	59	58	57	56	55	54	53
		↓	70	69	68	67	66	65	64	63	62
90	10	↑	79	78	77	76	75	74	73	72	71
		↓	88	87	86	85	84	83	82	81	80
108	12	↑	97	96	95	94	93	92	91	90	89
		↓	106	105	104	103	102	101	100	99	98
126	14	↑	115	114	113	112	111	110	109	108	107
		↓	124	123	122	121	120	119	118	117	116
144	16	↑	133	132	131	130	129	128	127	126	125
		↓	142	141	140	139	138	137	136	135	134
162	18	↑	151	150	149	148	147	146	145	144	143
		↓	160	159	158	157	156	155	154	153	152
180	20	↑	169	168	167	166	165	164	163	162	161
		↓	178	177	176	175	174	173	172	171	170
198	22	↑	187	186	185	184	183	182	181	180	179
		↓	196	195	194	193	192	191	190	189	188
216	24	↑	205	204	203	202	201	200	199	198	197
		↓	214	213	212	211	210	209	208	207	206

The diagrams can be small, so that when they are drawn for all three phases one above the other, the whole layout should still be of a convenient size. In all diagrams in Figs. 11 to 16, the full lines indicate the top sides of the coils and the broken lines indicate the bottom sides. The arrows indicate the instantaneous direction of current in the windings. The two-in and

one-out arrow check is used throughout the series. A small ellipse encloses conductors, or coil sides, that are in the same slot. The four phase leads are marked clearly at the bottom of each phase diagram, so slots that contain leads can easily be found merely by tracing a lead up to its slot.

All the connection diagrams used in this text are made for left-hand coils. Since it is assumed that the slots are numbered counterclockwise around the rotor, in the connection diagrams in Figs. 11 to 16, slot *1* is always the last slot at the left of *A*-phase group and the slots are counted from right to left. Lead A_1 is always the bottom lead from slot *1* and comes from the left-hand side of the slot.

When there are more than two conductors per slot, the top leads are taken from the top conductor at the right-hand side of the slot. The bottom leads are taken from the bottom conductor at the left-hand side. The best way to keep these facts straight is to memorize them.

Connection Tables

46. The connection diagrams become even more useful if they are used together with connection tables, such as Tables 3, 5, 7, 9, and 11. Each of these tables faces the connection diagram with which it is used.

For a specific job, it is not enough to know only the general pattern of the windings given in the connection diagram; the slots from which the phase leads emerge must also be determined. For each possible pole-and-slot combination, the connection tables indicate the slots for the 12 phase leads and the number of clips in the SP groups. Table 3, for example, supplements the 2-SPP connection diagram in Fig. 11, so that a complete diagram, like the one in Fig. 10, is not needed.

The data in the first two columns in Table 3 are the same as those in Table 1. Then, in Table 3, the number of slots is given for each of the 12 leads, with the bottom leads and the top leads indicated. The arrows in front of the slot numbers for

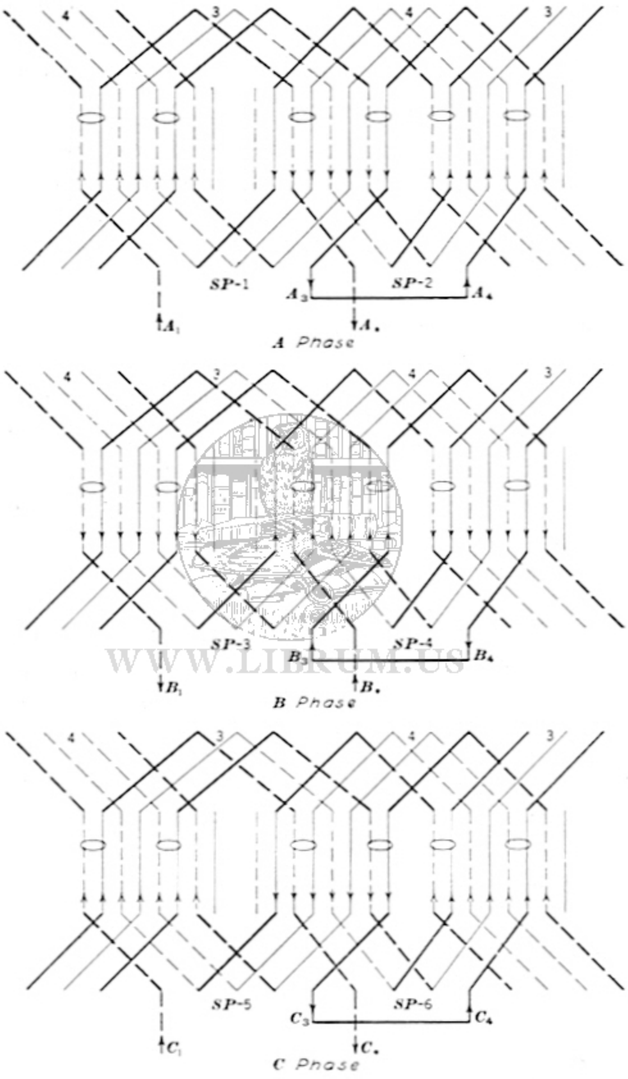


FIG. 13. CONNECTION DIAGRAM FOR $3\frac{1}{2}$-SPP-WINDINGS

TABLE 7

Connection Table for $3\frac{1}{2}$ Slots per Pole per Phase

Number of Poles	Number of Slots	A Phase				B Phase				C Phase				Short Pitch Number of Clips	
		Bottom Leads		Top Leads		Bottom Leads		Top Leads		Bottom Leads		Top Leads			
		A_1	A_2	A_3	A_4	B_1	B_2	B_3	B_4	C_1	C_2	C_3	C_4	SP 1-3-5	SP 2-4-6
4	42	↑1	32	30	20	↓15	4	2	34	↑29	18	16	6	3	2
6	63	↑1	53	51	41	↓57	46	44	34	↑29	18	16	6	3	2
8	84	↑1	84	82	72	↓57	46	44	34	↑29	18	16	6	3	2
10	105	↑1	94	92	82	↓36	25	23	13	↑71	60	58	18	3	2
12	126	↑1	116	114	104	↓36	25	23	13	↑92	81	79	69	3	2
14	147	↑1	137	135	125	↓57	46	44	34	↑113	102	100	90	3	2
16	168	↑1	158	156	146	↓57	46	44	34	↑113	102	100	90	3	2
18	189	↑1	179	177	167	↓57	46	44	34	↑134	123	121	111	3	2
20	210	↑1	200	198	188	↓71	60	58	48	↑141	130	128	118	3	2
22	231	↑1	221	219	209	↓78	67	65	55	↑155	144	142	132	3	2
24	252	↑1	242	240	230	↓78	67	65	55	↑176	165	163	153	3	2

Back pitch = 11 slots. Front pitch = 10 slots. Short pitch = 9 slots.

TABLE 8

CHECKING TABLE FOR 3½ SLOTS PER POLE PER PHASE

Number of Slots	Number of Poles	Polarity	*C* Phase				*B* Phase				*A* Phase			
42	4	↑	8	7	6	5		4	3	2	1	Z	Y	X
		↓		18	17	16	15	14	13	12		11	10	9
		↑	29	28	27	26		25	24	23	22	21	20	19
		↓		39	38	37	36	35	34	33		32	31	30
63	6	↑	50	49	48	47		46	45	44	43	42	41	40
		↓		60	59	58	57	56	55	54		53	52	51
84	8	↑	71	70	69	68		67	66	65	64	63	62	61
		↓		81	80	79	78	77	76	75		74	73	72
105	10	↑	92	91	90	89		88	87	86	85	84	83	82
		↓		102	101	100	99	98	97	96		95	94	93
126	12	↑	113	112	111	110		109	108	107	106	105	104	103
		↓		123	122	121	120	119	118	117		116	115	114
147	14	↑	134	133	132	131		130	129	128	127	126	125	124
		↓		144	143	142	141	140	139	138		137	136	135
168	16	↑	155	154	153	152		151	150	149	148	147	146	145
		↓		165	164	163	162	161	160	159		158	157	156
189	18	↑	176	175	174	173		172	171	170	169	168	167	166
		↓		186	185	184	183	182	181	180		179	178	177
210	20	↑	197	196	195	194		193	192	191	190	189	188	187
		↓		207	206	205	204	203	202	201		200	199	198
231	22	↑	218	217	216	215		214	213	212	211	210	209	208
		↓		228	227	226	225	224	223	222		221	220	219
252	24	↑	239	238	237	236		235	234	233	232	231	230	229
		↓		249	248	247	246	245	244	243		242	241	240

leads A_1, B_1, and C_1 correspond to the sequence indicated by the arrows on the connection diagrams. For example, the arrows for leads A_1 and C_1 point upward, or into the winding, and the arrows for B_1 point downward, or out of the winding.

Of the last two columns under the heading "Short Pitch, Number of Clips," the first column gives the clips in groups *SP-1*, *SP-3*, and *SP-5* – or, in short, *SP 1-3-5* – and the second, in groups *SP-2*, *SP-4*, and *SP-6* – or *SP 2-4-6*. The need for two SP columns arises from the fact that in windings with fractional values of SPP, the groups *SP 1-3-5* have one more clip than groups *SP 2-4-6*, as explained in Art. 41. This is true, of course, for windings with two conductors per slot. In windings with more than two conductors per slot, the rules explained in Art. 42 should be applied.

Consider, for example, a 10-pole 60-slot rotor, series-star connected, that has 2 SPP and 6 conductors per slot. Table 1 indicates that the connections for 2 SPP are given in Table 3. This table shows that phase A leads are in the following slots: A_1 in slot 1, A_2 in slot 55, A_3 in slot 54, and so on across the 10-pole line of the table. A better way to list these figures for actual use is as follows: A_1–*B1*, A_2–*B55*, A_3–*T54*, A_4–*T48*, and so on. Here the letters *B* and *T* stand for *bottom* and *top*.

In both SP columns, the numeral 1 appears; but for 6 conductors per slot, according to Table 2, there will be 5 clips in each SP group.

The method of checking the clips in the *SP* serves also as a check on the correct location of the various phase leads. In the example just given, leads No. 1 and No. 3, and leads No. 4 and star leads, in each phase should be 5 clips apart.

Use of Connection Tables

47. To illustrate the use of Fig. 11 and Table 3, let us consider the 2-SPP winding in Fig. 10. Usually, the winder sees the rotor fully wound and does not know any of the winding data except the number of rotor slots, which he obtains by

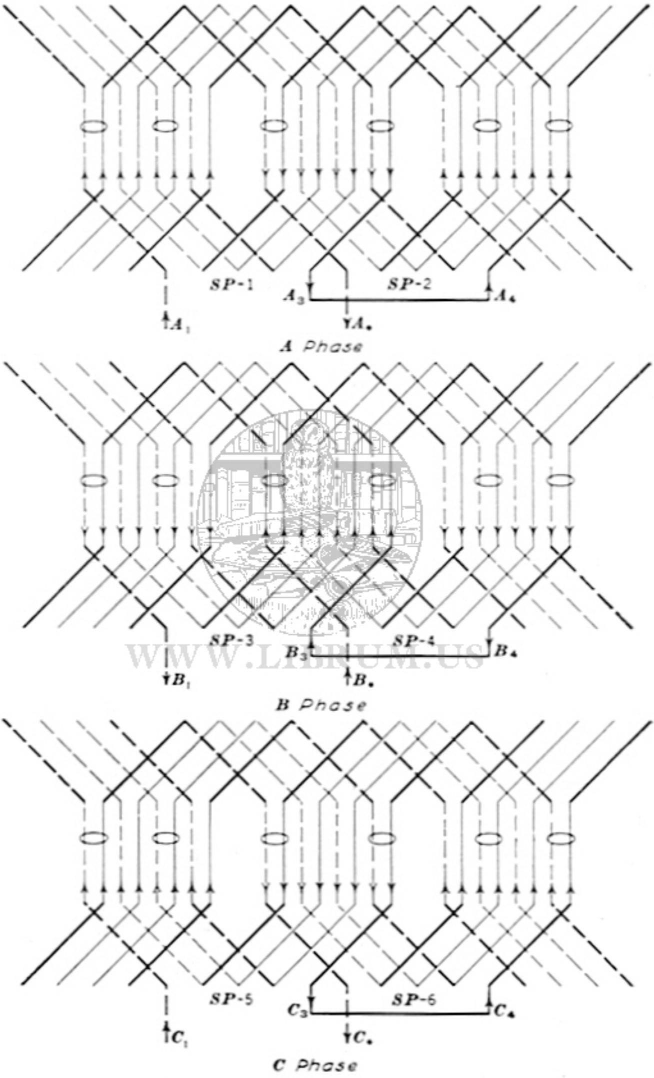


FIG. 14. CONNECTION DIAGRAM FOR 4-SPP WINDINGS

CONNECTION TABLE FOR FOUR SLOTS PER POLE PER PHASE

umber of Poles	Number of Slots	*A* Phase				*B* Phase				*C* Phase				Short Pitch Number of Clips	
		Bottom Leads		Top Leads		Bottom Leads		Top Leads		Bottom Leads		Top Leads			
		A_1	A_2	A_3	A_4	B_1	B_2	B_3	B_4	C_1	C_2	C_3	C_4	*SP* 1-3-5	*SP* 2-4-6
4	48	↑1	37	34	22	↓ 17	5	2	38	↑ 33	21	18	6	3	3
6	72	↑1	61	58	46	↓ 17	5	2	62	↑ 57	45	42	30	3	3
8	96	↑1	85	82	70	↓ 65	53	50	38	↑ 33	21	18	6	3	3
10	120	↑1	109	106	94	↓ 41	29	26	14	↑ 81	69	66	54	3	3
12	144	↑1	133	130	118	↓ 113	101	98	86	↑ 57	45	42	30	3	3
14	168	↑1	157	154	142	↓ 113	101	98	86	↑ 57	45	42	30	3	3
16	192	↑1	181	178	166	↓ 65	53	50	38	↑ 129	117	114	102	3	3
18	216	↑1	205	202	190	↓ 65	53	50	38	↑ 153	141	138	126	3	3
20	240	↑1	229	226	214	↓ 161	149	146	134	↑ 81	69	66	54	3	3
22	264	↑1	253	250	238	↓ 89	77	74	62	↑ 177	165	162	150	3	3
24	288	↑1	277	274	262	↓ 113	101	98	86	↑ 201	189	186	174	3	3

Back and front pitches = 12 slots. Short pitch = 11 slots.

TABLE 10

CHECKING TABLE FOR FOUR SLOTS PER POLE PER PHASE

Number of Slots	Number of Poles	Polarity	*C* Phase				*B* Phase				*A* Phase			
48	4	↑	9	8	7	6	5	4	3	2	1	Z	Y	X
		↓	21	20	19	18	17	16	15	14	13	12	11	10
		↑	33	32	31	30	29	28	27	26	25	24	23	22
		↓	45	44	43	42	41	40	39	38	37	36	35	34
72	6	↑	57	56	55	54	53	52	51	50	49	48	47	46
		↓	69	68	67	66	65	64	63	62	61	60	59	58
96	8	↑	81	80	79	78	77	76	75	74	73	72	71	70
		↓	93	92	91	90	89	88	87	86	85	84	83	82
120	10	↑	105	104	103	102	101	100	99	98	97	96	95	94
		↓	117	116	115	114	113	112	111	110	109	108	107	106
144	12	↑	129	128	127	126	125	124	123	122	121	120	119	118
		↓	141	140	139	138	137	136	135	134	133	132	131	130
168	14	↑	153	152	151	150	149	148	147	146	145	144	143	142
		↓	165	164	163	162	161	160	159	158	157	156	155	154
192	16	↑	177	176	175	174	173	172	171	170	169	168	167	166
		↓	189	188	187	186	185	184	183	182	181	180	179	178
216	18	↑	201	200	199	198	197	196	195	194	193	192	191	190
		↓	213	212	211	210	209	208	207	206	205	204	203	202
240	20	↑	225	224	223	222	221	220	219	218	217	216	215	214
		↓	237	236	235	234	233	232	231	230	229	228	227	226
264	22	↑	249	248	247	246	245	244	243	242	241	240	239	238
		↓	261	260	259	258	257	256	255	254	253	252	251	250
288	24	↑	273	272	271	270	269	268	267	266	265	264	263	262
		↓	285	284	283	282	281	280	279	278	277	276	275	274

counting. Then he has to establish the SPP value from the rotor. Assume also that there are two conductors per slot. The winder can determine this fact visually.

The winder will find one clip in each SP group and 4 clips between each No. 3 and star lead. He will conclude that the SPP $= 1 + 1 = 2$, or by positive check, SPP $= \frac{4}{2} = 2$. Therefore, he should use Table 3 and the connection diagram in Fig. 11.

Since he counted 24 slots, there must be four poles in the stator, because, according to Table 1, this is the only possible combination. Four poles immediately suggest $\frac{24}{4} = 6$ slots in the back and front pitch, and 5 slots in the short pitch. Note that all the combinations for 2 SPP have the same pitches.

One of the free bottom leads is the line lead A_1. The slot from which it emerges is the slot *1*. Other slots are marked counterclockwise around the rotor. Table 3 indicates that the other free leads for phase *A* emerge from slots *19*, *18*, and *12*; for phase *B*, from slots *9*, *3*, *2*, and *20*; and for phase *C*, from slots *17*, *11*, *10*, and *4*. Since the winding pitch is known, the winder needs only a connection diagram, such as the one in Fig. 11, to give him all the information he needs. The diagram in Fig. 11 indicates only one clip at SP slots, and Table 3 indicates that it has to be between leads A_1 and A_3, or between leads emerging from slots *1* and *18* for phase *A*. A similar SP group will be between leads B_1 and B_3, or between the bottom lead from slot 9 and the top lead from slot *2*; and for phase *C*, between the bottom lead from slot *17* and the top lead from slot *10*.

These leads may be tested and reconnected, with frequent reference to Table 3 and Fig. 11. A complete diagram like the one in Fig. 10 is not needed and would represent unnecessary loss of time and effort. It is, however, assumed that the winder has a thorough understanding of the meaning of connection diagrams and tables.

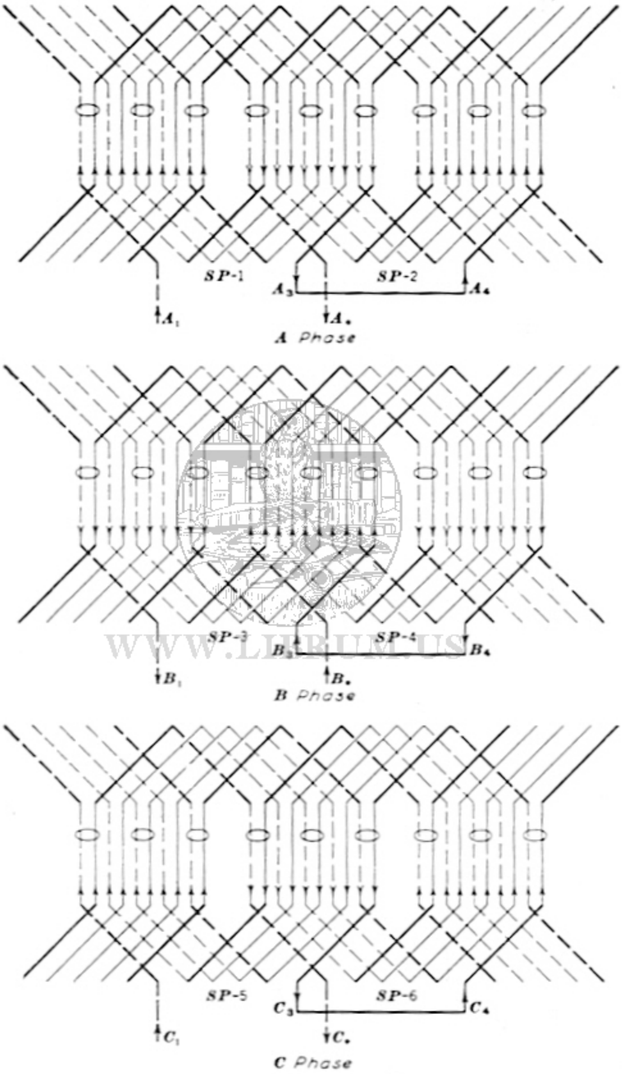


FIG. 15. CONNECTION DIAGRAM FOR 5-SPP WINDINGS

TABLE 11

Connection Table for Five Slots per Pole per Phase

Number of Poles	Number of Slots	A Phase				B Phase				C Phase				Short Pitch Number of Clips	
		Bottom Leads		Top Leads		Bottom Leads		Top Leads		Bottom Leads		Top Leads			
		A_1	A_2	A_3	A_4	B_1	B_2	B_3	B_4	C_1	C_2	C_3	C_4	*SP* 1-3-5	*SP* 2-4-6
4	60	↑ 1	46	42	27	↓ 21	6	2	47	↑ 41	26	22	7	4	4
6	90	↑ 1	76	72	57	↓ 21	6	2	77	↑ 71	56	52	37	4	4
8	120	↑ 1	106	102	87	↓ 81	66	62	47	↑ 41	26	22	7	4	4
10	150	↑ 1	136	132	117	↓ 51	36	32	17	↑ 101	86	82	67	4	4
12	180	↑ 1	166	162	147	↓ 141	126	122	107	↑ 71	56	52	37	4	4
14	210	↑ 1	196	192	177	↓ 141	126	122	107	↑ 71	56	52	37	4	4
16	240	↑ 1	226	222	207	↓ 81	66	62	47	↑ 161	146	142	127	4	4
18	270	↑ 1	256	252	237	↓ 111	96	92	77	↑ 191	176	172	157	4	4
20	300	↑ 1	286	282	267	↓ 201	186	182	167	↑ 101	86	82	67	4	4
22	330	↑ 1	316	312	297	↓ 111	96	92	77	↑ 221	206	202	187	4	4
24	360	↑ 1	346	342	327	↓ 261	246	242	227	↑ 131	116	112	97	4	4

Back and front pitches = 15 slots. Short pitch = 14 slots.

TABLE 12

CHECKING TABLE FOR FIVE SLOTS PER POLE PER PHASE

Number of Poles	Polar-ity	C Phase					B Phase					A Phase				
4	↕	11	10	9	8	7	6	5	4	3	2	1	Z	Y	X	W
		26	25	24	23	22	21	20	19	18	17	16	15	14	13	12
	↕	41	40	39	38	37	36	35	34	33	32	31	30	29	28	27
		56	55	54	53	52	51	50	49	48	47	46	45	44	43	42
6	↕	71	70	69	68	67	66	65	64	63	62	61	60	59	58	57
		86	85	84	83	82	81	80	79	78	77	76	75	74	73	72
8	↕	101	100	99	98	97	96	95	94	93	92	91	90	89	88	87
		116	115	114	113	112	111	110	109	108	107	106	105	104	103	102
10	↕	131	130	129	128	127	126	125	124	123	122	121	120	119	118	117
		146	145	144	143	142	141	140	139	138	137	136	135	134	133	132
12	↕	161	160	159	158	157	156	155	154	153	152	151	150	149	148	147
		176	175	174	173	172	171	170	169	168	167	166	165	164	163	162
14	↕	191	190	189	188	187	186	185	184	183	182	181	180	179	178	177
		206	205	204	203	202	201	200	199	198	197	196	195	194	193	192
16	↕	221	220	219	218	217	216	215	214	213	212	211	210	209	208	207
		236	235	234	233	232	231	230	229	228	227	226	225	224	223	222
18	↕	251	250	249	248	247	246	245	244	243	242	241	240	239	238	237
		266	265	264	263	262	261	260	259	258	257	256	255	254	253	252
20	↕	281	280	279	278	277	276	275	274	273	272	271	270	269	268	267
		296	295	294	293	292	291	290	289	288	287	286	285	284	283	282
22	↕	311	310	309	308	307	306	305	304	303	302	301	300	299	298	297
		326	325	324	323	322	321	320	319	318	317	316	315	314	313	312
24	↕	341	340	339	338	337	336	335	334	333	332	331	330	329	328	327
		356	355	354	353	352	351	350	349	348	347	346	345	344	343	342

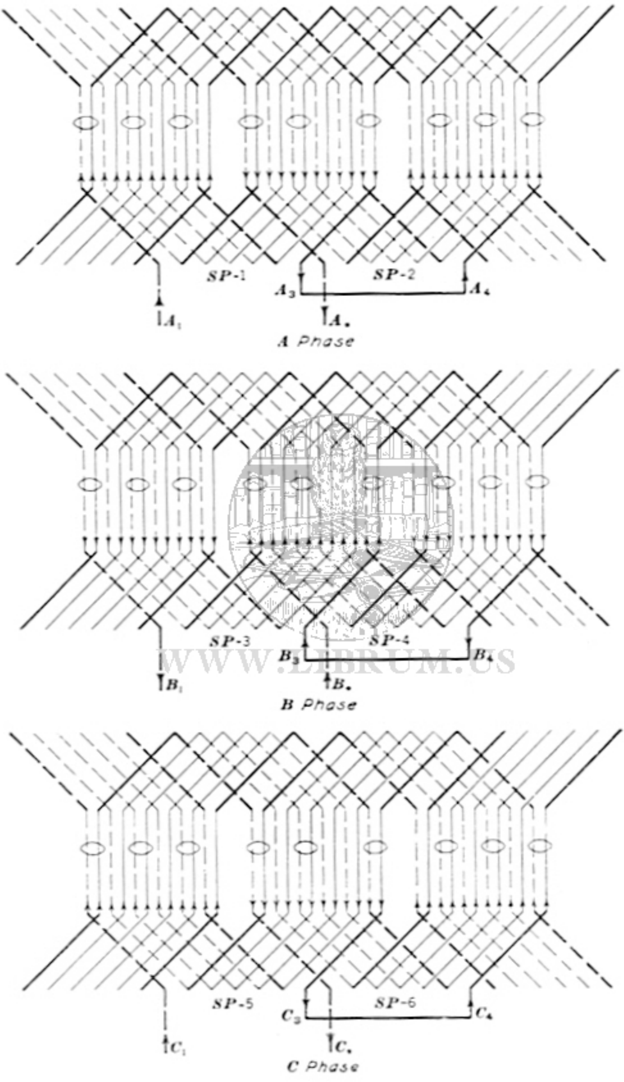
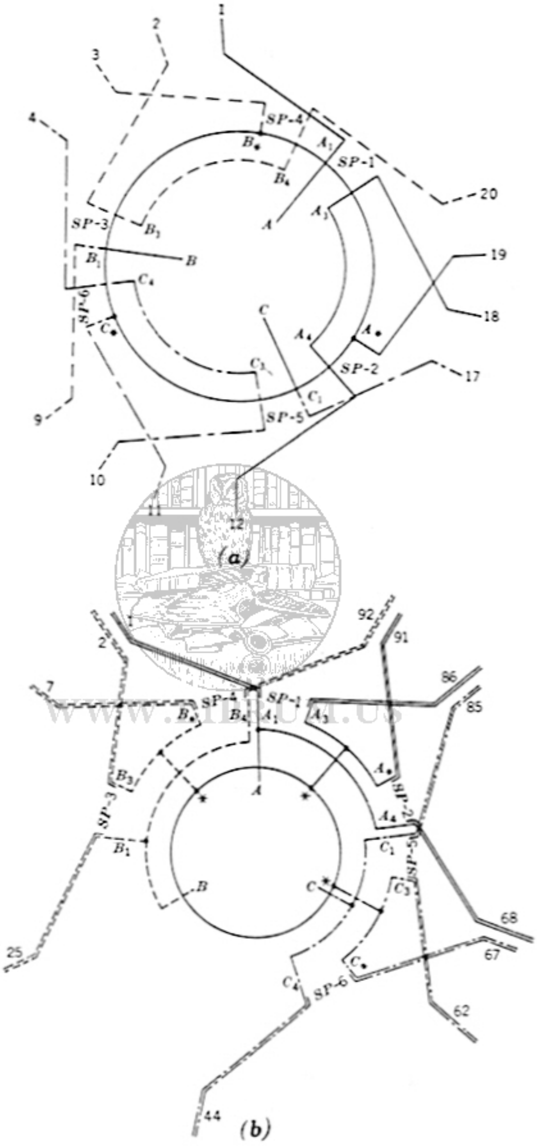


Fig. 16. Connection Diagram for 6-SPP Windings



(a) Diagram for 2-SPP 24-slot 4-pole winding
(b) Diagram for 6-SPP 108-slot 6-pole winding

FIG. 17. WORKING DIAGRAMS

Working Diagrams

48. For satisfactory repair and reconnecting work, it is necessary to have a working diagram of the connections. The working diagram is prepared by using data from the connection diagram and the corresponding connection table. The repairman prepares first the connection diagram and then the working diagram, which should be as simple as possible. The working diagram for the 24-slot 4-pole wave winding in Figs. 10 and 11 is shown in Fig. 17*(a)*. Only the slots from which the 12 phase leads are taken should be indicated on the working diagram. The slots are not drawn, only indicated by the slot number taken from Table 3. The six SP groups are marked in their proper positions by their symbols *SP-1* to *SP-6*. This winding is series-star connected, and the common star connection is indicated by a star ring connecting all star leads. The line leads are extended to the line terminals *A*, *B*, and *C*. A shorter line, such as at A_1 and A_2, indicates a bottom lead; and a longer line, such as at A_3 or A_4, indicates a top lead. Only the coils with phase leads are indicated; for phase *A*, they are shown by full lines; for phase *B*, by broken lines; and for phase *C*, by dot-and-dash lines. In order to indicate short pitches, the coils are bent to a shorter throw.

An illustration of a working diagram of a relatively complicated wave winding is given in Fig. 17*(b)*. It is a 6-SPP winding, as in Fig. 16, for a 108-slot rotor with 4 conductors per slot, wound for 6 poles and parallel-star connected. The four conductors per slot are indicated by double lines representing coils. The connection table for this winding is not given in this text. It is readily seen that the back and front pitches are $\frac{108}{6} = 18$ slots, that the short pitches are 17 slots, and that the winding pitch is 36 slots.

A working diagram can be made out for any winding for which the connection diagram and the connection table are available. It will be good practice to prepare working diagrams

for several windings for which the connection diagrams and tables are given in this text.

Checking Tables for Connection Diagrams

Purpose of Checking Tables

49. The connection diagrams and tables, and the working diagrams, indicate the phase leads of the windings but do not indicate which slots contain the coils of a phase, or which coils are connected together to form the coil series in the six phase sections. This information is given in the checking table, which should be used together with the connection diagram and the connection table for each winding.

Table 4, for example, is a checking table prepared for 2-SPP windings and should be used with the diagram in Fig. 11 and with Table 3; Table 6 corresponds to 3-SPP windings in Fig. 12 and Table 5; Table 8 corresponds to $3\frac{1}{2}$-SPP windings in Fig. 13 and Table 7; Table 10 corresponds to 4-SPP windings in Fig. 14 and Table 9; and Table 12 corresponds to 5-SPP windings in Fig. 15 and Table 11. There is no checking table included here for Fig. 16. For convenience of reference, the connection diagram, the connection table, and the checking table for each SPP value are grouped together.

The diagrams in Figs. 11 to 16 inclusive have been laid out for a 120-deg spacing of the three groups of phase leads. Most wave windings used on rotors have this spacing. The checking tables enable the repairman to change this spacing to a closer one, if that is required. Such tables also permit the addition of slot combinations.

Structure of Checking Tables

50. A description of each checking table is important for a complete understanding of the table. The specific description of each successive table will, however, include only the points which are different from the ones described for the preceding table or tables. A statement that applies, for example, to Tables

8, 10, and 12 will be given for Table 8 and will not be repeated for Tables 10 and 12.

The first two columns in each checking table give the number of slots and poles which might be used with the specified SPP value.

The third column indicates polarity; each arrow shows the direction of current in the coils placed in slots indicated in the same horizontal line; these arrows correspond with arrows in the connection diagrams and tables.

The following columns include the numbers of all slots containing a coil from phases *A*, *B*, and *C*, as indicated by the column headings. Since all the connection diagrams have the A_1 lead in the bottom of slot *1* and are numbered counterclockwise, the checking tables put the *A* phase at the right, with the phases and slot numbers running consecutively from right to left.

Each horizontal line of slot numbers indicates the slots which contain coils under one pole; the number of lines in the table indicates the number of poles in the machine. For example, if the machine has a total of only four poles for 2 SPP, only the first four lines of Table 4 will apply to this machine; for a machine with 6 poles using a 2-SPP rotor winding, the first six lines of Table 4 will apply; for a machine with 20 poles for 2 SPP, the first 20 lines in Table 4 will apply. Checking tables in this text indicate for each SPP value an increase in poles in steps of two poles by the addition of two lines in the table.

Each vertical column of slot numbers under the headings "Phase *A*," "Phase *B*," and "Phase *C*" indicates the slots carrying coils which belong to this phase. The number of columns under a phase heading indicates the number of coils per pole per phase.

Each group of slots in any one horizontal line under a phase heading is called a pole-phase group. For example, in Table 4 there are three pole-phase groups in each line, each containing two slots. If the winding has an integral value of SPP, each

pole-phase group contains the same number of slots, or the winding is said to have an even distribution of pole-phase groups.

Checking Table for 2 SPP

51. In Table 4, the checking table for 2 SPP, the first number, starting from the right, in the first line is 1. This number represents slot *1* on the core. The letter Z to the right of this number represents the ending of the circle of slots on the core, or the last slot. For example, for the 4-pole 24-slot machine, substitute 24 for Z; for the 6-pole 36-slot machine, $Z = 36$; for the 144-slot rotor, $Z = 144$. Note that the number to be used as Z is the number from the column indicating the total number of slots in the rotor for a particular number of poles.

For a 4-pole 24-slot machine, after Z is replaced by 24, Table 4 indicates six slot numbers in each of the first four lines; two slots for each pole-phase group. These numbers do not change for any machine which has the same SPP. In other words, a 4-pole machine as well as a 24-pole machine will have in slot *3* a coil which belongs to phase B, and the direction of current in this coil will be into the winding.

When Table 4 is compared with the complete diagram in Fig. 10, it is seen that the table gives the same information as this diagram. The coils in slots *1*, *7*, *13*, and *19* make the first series in phase A, and the coils in slots *24*, *6*, *12*, and *18* make the second series. The checking table, however, does not indicate the phase leads; they have to be taken from the connection table, Table 3 for 2 SPP, when the working diagram is being prepared. It is also implied that the short pitch will have to be used to connect coils from slots *19* and *24* between the two series. This information, however, is found in the connection table and not in the checking table.

As the discussion so far has shown, it is important to use the connection diagram, the connection table, and the checking table simultaneously for each SPP value. When this is

done, the working diagram can be prepared without difficulty. This method has proved simpler than referring to one complete diagram, which might contain too many lines to be helpful.

Checking Table for 3 SPP

52. For the integral value of 3 SPP, as in Table 6, each pole-phase group contains three slots and has an even distribution of pole-phase groups. The letter Z in the first line represents the last slot of the total slots used; the letter Y similarly represents the next to the last slot. For example, for a 36-slot rotor and 4 poles, $Z = 36$ and $Y = 35$, while for the 126-slot rotor and 14 poles, $Z = 126$ and $Y = 125$, and so on.

Table 6 should be used together with Fig. 12 and Table 5.

Checking Table for $3\frac{1}{2}$ SPP

53. Table 8 is the checking table prepared for $3\frac{1}{2}$ SPP. The letters Z, Y, and X stand for the last three slots used in a particular winding. For example, for 42 slots and 4 poles, $Z = 42$, $Y = 41$, and $X = 40$.

Since this table is concerned with a fractional value of SPP, the number of slots in successive pole-phase groups is not the same. Every other group has one slot less, which is indicated by the blank spaces in the table, such as between slots 4 and 5. In the first line of Table 8, the three pole-phase groups have therefore four, three, and four slots, respectively, or in short, an odd grouping of 4-3-4 slots. All checking tables with blank spaces indicate a fractional SPP value and an odd distribution of pole-phase groups.

Table 8 should be used in connection with Fig. 13 and Table 7.

Checking Tables for 4 and 5 SPP

54. Tables 10 and 12 have been prepared for windings with integral numbers of SPP and therefore do not have blank spaces. Table 10, for 4 SPP, has four slots for each pole-phase

group, and Table 12 has five slots. The letter W in the first line of Table 12 stands for the fourth-last slot used for a specific winding. For example, for a winding with 240 slots and 16 poles, $Z = 240$, $Y = 239$, $X = 238$, and $W = 237$.

Extending of Tables

55. The checking tables and connection tables given in this text may be extended for a greater number of slots and thus for more combinations with various numbers of poles. The number of poles can be increased in steps of two. If, for example, an additional combination is required in Tables 11 and 12, it will represent 26 poles. The corresponding number of slots can be found by adding six times the SPP to the preceding total number of slots. Table 11 has 5 SPP, and so $6 \times 5 = 30$ slots should be added to the last total number of slots, which is 360. Thus, $360 + 30 = 390$ slots should be used with 26 poles in the next combination for 5 SPP.

Another method of extending the tables is to examine the difference between successive total numbers of slots in the first column of the checking tables and then to add that number for each pair of poles needed. In Table 12, the difference is 30, so $360 + 30 = 390$ slots for 26 poles, $390 + 30 = 420$ slots for 28 poles, and so on.

It is also possible to prepare tables which are not given in this text. For example, by comparing Tables 5, 7, and 9, you can see how the connection table was prepared for $3\frac{1}{2}$ SPP from the tables for 3 SPP and 4 SPP. By the same rule, a connection table may be prepared for $4\frac{1}{2}$ SPP by using Tables 9 and 11. Of course, Table 1 is also always useful for rechecking new tables.

Main Features of Wave Windings

56. Now that the connection diagrams and tables used with wave windings have been discussed, let us summarize the main characteristics of wave windings:

Wave windings for three-phase a-c motors, whether used on a rotor or a stator, use coils with ends bent away from the coil center line. The adjacent coils ends are connected by clips to form a series of coils which goes around the core. The commutator is not used and the winding is always retrogressive. Each series has half as many coils as there are poles. Several series of coils make a phase section, the number of coils in a section depending on the SPP value. Each phase has two such sections; that is, the winding always has six sections. The twelve phase leads of these six sections should be connected properly in star or delta.

If the value of slots per pole per phase has been determined and the number of poles in the motor is known, the winding may be fully checked or rewound.

Phase Coils

Need for Phase Coils

57. Another characteristic feature of wave windings is the placement of phase coils. Their proper location is very important to the winding procedure.

When an a-c wave winding has more than two conductors per slot, some slots hold conductors from two different phases. Such conductors and their coils come at the beginning and the end of each pole-phase group and are called phase coils and phase conductors.

The total number of phase coils in any three-phase wave winding is always equal to six times the number of poles, or twice the number of pole-phase groups. Because the voltage between phase coils is full phase value, the insulation on their ends is reinforced and is called phase insulation. The phase coils are therefore easily recognized by the increased insulation at their ends.

Unlike the coil ends, however, the slot portions of all coils

are insulated alike, since their ground insulation is more than that required for protection against phase voltage.

When the winding has only one or two conductors per slot, crossing coil ends, at both ends of the pole-phase groups, also need and receive phase insulation.

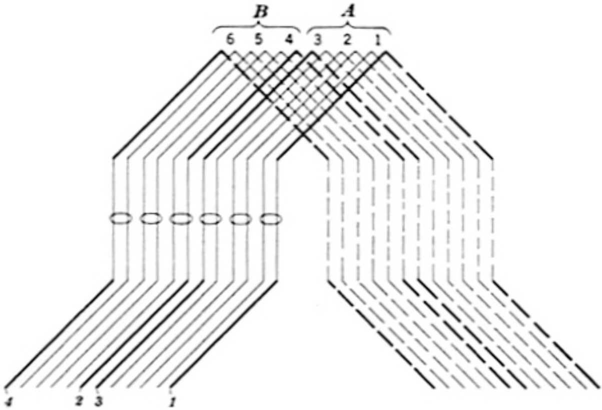
If the extra insulation on any group of conductors in a phase-coil slot is placed properly, it will protect both top and bottom end conductors and, as far as it goes, top and bottom leads too. The first purpose of such extra insulation is to separate the top and bottom coil ends, which are in different phases and have phase voltage between them; at the same time, it also gives protection to other coil parts. The coil ends coming from other slots have less than phase voltage across them.

Indication of Phase Coils

58. In connection diagrams, Fig. 11 through 16, the phase coils are indicated by heavier lines than plain coils. In Table 6, a heavy black dot above a column indicates that all coil ends coming out of the slots in that column have an extra phase insulation. In the first line of Table 6, the slots containing coil ends with phase insulation are, from right to left, slots *35*, *1*, *2*, *4*, *5*, and *7*; in the last line, such slots are *206*, *208*, *209*, *211*, *212*, and *214*. The dots are, however, not repeated in other checking tables; they are given here merely as an example. The end columns of each phase in checking tables indicate the slots which contain phase coils if more than two conductors per slot are used.

Right-Hand and Left-Hand Phase Coils

59. When a slot contains only two conductors, these conductors are placed one above the other and their sides are either top or bottom sides. However, when there are four or more conductors in the same slot, two conductors are placed next to each other, the next pair on top of them, and so on. The



1 to 6. slot numbers
1, 2. right-hand phase coils
3, 4. left-hand phase coils

A, B. pole-phase groups

FIG. 18. PHASE COILS

conductor at the left side of the slot is called the left-hand coil and the conductor at the right side is the right-hand coil. The total number of phase coils in a winding is always divided into an equal number of right-hand phase coils and left-hand phase coils. During the winding, the winder must be especially careful to place the right-hand and left-hand phase coils properly.

A part of a winding with 3 SPP and three slots in each pole-phase group is shown in Fig. 18. The winding has four conductors per slot, or two conductors per coil. The coils, each represented by two conductors, are marked by their slot numbers 1 to 6, and the pole-phase groups are lettered *A* and *B*. Group *A* starts with the right-hand coil *1*, and group *B* with the right-hand coil *2*. Group *A* ends with the left-hand coil *3* and group *B* with the left-hand coil *4*. All four coils, *1* to *4*, are phase coils and carry additional insulation. Only two top conductors in a slot are indicated in Fig. 18 by the ellipses which enclose conductors from the same slot. Two more conductors

(not shown) will be placed in each slot. Since the coils *1* to *4* were the coils at the end of one pole-phase group, the other two coils in the same slot with them will belong to the next pole-phase group. The coils *1* to *4* are therefore phase coils and carry phase insulation, as indicated by the heavy lines in Fig. 18.

Standard-Lead and Short-Lead Phase Coils

60. The phase coils shown in Fig. 18 have standard-length leads and are classified as *standard-lead left-hand* and *standard-lead right-hand phase coils.*

In large windings using conductors of heavy strap, the phase-coil problem is more complicated, because at six points in the winding the SP connections require that some phase coils have the top lead short, while others have the bottom lead short. As a result, there will be some *short-bottom-lead right-hand phase coils, short-top-lead right-hand phase coils, short-bottom-lead left-hand phase coils, and short-top-lead right-hand phase coils.*

These phase coils, in addition to the two types of standard-lead phase coils, make six types of phase coils. The winder has to be very careful to place each type properly.

Identifying Phase Coils

61. As mentioned earlier, phase coils may be identified in almost any winding by the extra insulation on their ends. This insulation makes the end sections of the coils thicker. Sometimes an identifying number is stamped on the lead end of the strap, different numbers being used for right-hand and left-hand coils. The rest of the coils, which are called plain coils, are all insulated alike.

The checking tables will help in determining the position of phase coils. The slots and pole-phase groups are all laid out in the tables in the same order as the actual coils. Hence, these tables may be used to check the coil grouping, to locate the

slots that carry the phase coils and their extra insulation, and also to locate the slots for short-lead phase coils.

When the SPP value is integral, such as 3 SPP in Table 6, all coil groups contain the same number of coils. The end coils in each group are possible phase coils, as indicated by the black dots.

When the SPP value is fractional, such as $3\frac{1}{2}$ SPP in Table 8, the table has blank spaces and every second coil group has one coil less than the groups on either side. This fact should be carefully considered when determining the phase coils. The possible phase coils, however, are again the end coils of each pole-phase group, but the number of plain coils between them varies for every other group.

Finding Number of Slots in SP Groups

62. For both odd and even coil grouping, the number of slots in the space over any SP connection should be twice the number of slots per pole per phase.

For example, for an even coil grouping and integral SPP, Table 3 for 2 SPP places the leads A_1 and A_2 for 4 poles and 24 slots in slots *1* and *19*. The SP connection *SP*-1 must therefore be between slots *19* and *24*, giving a pitch of 5 slots. There are actually four slots between slots *19* and *24*, or double the number of SPP for this winding. Table 3 also indicates leads A_3 and A_4 in slots *18* and *12*; the SP connection *SP-2* is between slots *18* and *13*, and there are four slots between slots *18* and *13*. The number of slots in this example may be rechecked against the complete diagram in Fig. 10.

As an example of odd coil grouping and fractional SPP, take a 4-pole 42-slot winding with $3\frac{1}{2}$ SPP, as in Table 7. The phase leads B_3 and B_4 come from slots *2* and *34*. The SP connection *SP-4* between them has two connections: one is from slot *2* to slot *36*. Between this pair of slots are 7 slots, or double $3\frac{1}{2}$ SPP. Now take leads B_1 and B_2. Their leads come from slots *15* and *4*, and the SP connection *SP-3* between them is

from slot *12* to slot *5*. Between slots *12* and *5* are only 6 full slots, but each conductor is alone in its slot, so to 6 full slots must be added 2 half slots, making the equivalent of 7 full slots.

Winding of Wave-Wound Rotors

Preparation for Rewinding of Rotor

Preparation for Stripping

63. The procedure for placing a new wave winding on a rotor is, in principle, the same as that for rewinding an old winding. Yet, in addition to the placement of windings, a rewinding job includes the stripping of old windings and the repairing of coils and connections. Such stripping can result in a great deal of trouble if not handled properly. Therefore, some brief, practical suggestions are given here for stripping and rewinding a wave-wound rotor.

As the first step, before starting the actual stripping, determine the number of phases, poles, slots, and slots per pole per phase, and the type of connection, and put this data on paper. Then, using the data determined, select the diagram and tables that apply to the job.

Next, examine the winding for SP leads and phase coils. If the winding has phase coils, find out which ones are right-hand coils and which left-hand coils, and whether they have standard or short leads.

Also, before stripping any rotor winding, study the lead arrangement at the six SP locations. If the short-lead coils must be replaced exactly as they are, mark them and make any notes necessary. If short-lead coils are mixed with other coils, a few leads entirely too short for connection are likely to show up after all coils have been put back into place. The number of slots, the diameter of the rotor, and the size of the

strap in the coils may make it possible to disregard this matter, but usually it pays to find and mark the short-lead coils.

Marking Old Windings

64. The simplest and perhaps the best way to mark an old winding is to find the A_1 lead, mark its slot suitably, stamp it with the figure 1, and then go around the winding counterclockwise, stamping the top side of every top lead with its proper number. Other methods of marking depend on the winding and the dies or other tools available for marking at the repair shop.

Putting extra markings on the main leads and phase-coil leads will help you to insulate them properly after they have come out of the slots.

Finding No. 1 Leads in Winding with Integral SPP

65. On a job that has just come in for repair, and in checking a completed winding, the first step is to find the proper slots for the No. 1, or line, leads of the three phases.

It is assumed that the SPP value is known and that it is an integral number. For the purpose of discussion, assume the value 3 SPP. The check of the winding will be easy if the connection diagram in Fig. 12 and Tables 5 and 6 are kept ready for reference.

The line leads are easy to recognize. They are all bottom leads and are used to connect the winding to the slip rings. Since the winding has been disconnected, the leads are free. The first free bottom lead is A_1 and its slot is slot *1*. The slot and lead should be marked properly.

In order to find the lead B_1, the slots should be counted counterclockwise from slot *1*.

In Table 6, slot *1* is in the left-hand column under the heading "Phase A," and the polarity of the coil lead A_1 is indicated by the upward, or inward, arrow. The lead B_1 will be in one of the slots grouped in the left-hand column under the

heading "Phase B." It must be a slot with the polarity arrow pointing downward, or outward, such as slots *13* and *31*. Table 5 gives the same information.

Now, the slots are counted counterclockwise around the rotor, starting from slot *1*. If the bottom lead from slot *49* is free, it is the lead B_1. From Table 5, it is seen that this is a winding for 72 slots and 8 poles. This procedure illustrates how the use of tables simplifies checking. The exact number of slots and poles has been determined by actually counting only the slots between A_1 and B_1.

The remaining free bottom lead is C_1. It is emerging from slot *25*. As a double check, Table 6 should be consulted. Lead C_1 has to come from one of the slots in the left-hand column under the heading "Phase C," and the arrow indicating polarity must point upward. Table 6 shows that slot *25* is one of possible slots, but Table 5 indicates definitely that, for 8 poles, slot *25* contains the coil with the lead C_1.

Finding No. 1 Leads in Winding with Fractional SPP

66. Assume a winding with $3\frac{1}{2}$ SPP and apply Fig. 13 and Tables 7 and 8. As seen in Fig. 13, each group of coils in the diagram has an extra slot which does not contain a coil. The coil groups will have 3 and 4 coils alternately to give an average of $3\frac{1}{2}$ coils in a group. The numerals 3 and 4 in Fig. 13 indicate this fact.

After the lead A_1 and the slot *1* have been selected and marked on the rotor, Table 8 indicates that the lead B_1 could come from any of the slots in the left-hand column of the four columns under the heading "Phase B," such as slots *15*, *36*, *57*, and so on. The extra slots should *not* be counted. If the free lead B_1 is found on the rotor, counting counterclockwise up to the slot *36*, Table 7 indicates that the winding is for 10 poles and 105 slots. As a check, the lead C_1 must then come from the slot *71*. If it does, the procedure of finding the leads was correct.

Finding Star Leads

67. For both integral and fractional SPP values, each star lead is a bottom lead from the slot that is one back pitch behind the slot containing the line lead of the same phase.

For example, for a 3-SPP winding, Table 5 indicates a back pitch of 9 slots. For the winding with 72 slots and 8 poles discussed in Art. 65, counting 9 slots backwards from slot *1* gives slot *64*; so, lead A_* must come from slot *64*. The same information is confirmed by Table 5. Lead B_* comes from the slot which is 9 slots behind slot *49*, or from slot *40*; and lead C_* comes from the slot which is 9 slots behind slot *25*, or from slot *16*. All these facts are confirmed by Table 5.

As an example of a fractional SPP value, take the winding discussed in Art. 66. Table 7 indicates a back pitch of 11 slots. Note that the front pitches are one slot shorter for fractional SPP. If for 105 slots and 10 poles, the lead A_1 comes from slot *1*, the lead A_* comes from slot *94*, the lead B_* from slot *25* (36 − 11) and lead C_* from slot *60* (71 − 11). In Table 7, the arrows for the star leads should always point in the direction opposite that of the arrows for the line leads.

Finding No. 3 Leads

68. For all SPP values, the No. 3 lead is always the top lead from a slot that is always back of the slot containing the star lead of the same phase. Each No. 3 lead is back of its star lead by a number of slots equal to one less than the full number of slots per pole per phase; with fractional pitch, the fraction is ignored. Thus for 2 SPP or $2\frac{1}{2}$ SPP the No. 3 lead is one slot back, for 3 SPP or $3\frac{1}{2}$ SPP it is 2 slots back, and so on.

For example, in the 3-SPP winding with 72 slots and 8 poles, the No. 3 leads are two slots back of the slots for star leads, or A_3 comes from slot *62* (64 − 2), B_3 from slot *38* (40 − 2), and C_3 from slot *14* (16 − 2). For the $3\frac{1}{2}$-SPP winding with 105 slots and 10 poles, A_3 comes from slot *92* (94 − 2), B_3 from slot *23* (25 − 2), and C_3 from slot *58* (60 − 2).

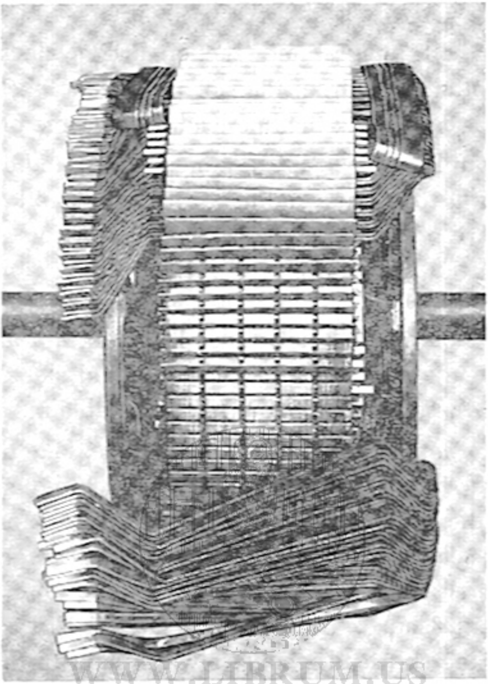


FIG. 19. START OF WAVE WINDING

Finding No. 4 Leads

69. For all SPP values, the No. 4 lead is always the top lead from a slot that is always back of the slot for the No. 3 lead by a number of slots equal to the front pitch.

For example, for the 3-SPP winding, the No. 4 slots will be 9 slots behind the No. 3 leads, and in the $3\frac{1}{2}$-SPP winding they will be 10 slots behind. The values may be verified in Tables 5 and 7.

In determining the phase leads of a winding, remember to check the polarities of the leads as well as the slot numbers. The polarities are indicated by arrows in connection diagrams and in connection and checking tables.

Rewinding Rotors with Standard Leads and No Phase Coils

Arranging Coils

70. An example of a job started correctly is shown in Fig. 19. It is a three-phase wave winding for a 144-slot rotor with 12 poles.

Dividing 144 slots by the number of poles and then dividing the result by the number of phases gives 4 SPP, or $\frac{144}{12 \times 3} = 4$ SPP. Tables 9 and 10 and Fig. 14 apply to this job, giving 12 slots for the back pitch. The illustration shows four conductors per slot, or two pairs of straps in parallel, so that there are actually two conductors per slot. The first of the upper slots have only two bottom conductors in place.

This winding has no phase coils; the straps are all insulated alike. It also has standard leads on all coils because the straps are not heavy enough to need short-lead coils. The winding can be started in any slot, and no data other than the back pitch are needed until all coils are in the slots. Assuming that the repairman is careful and that the coils are made up properly, the coils themselves and the back pitch are enough to get them into place correctly.

Before rewinding, lay the coils out in order. Start with the coil that belongs to slot *1*, or the No. 1 coil, on the bottom of the pile and end with the last coil. Put the last coil back in the slots first, with its bottom coil side in the first slot to the right of the A_1 slot. Then rewind to the right, the No. 1 coil going in last.

Finding Phase Leads

71. After all coils are in place, twelve phase leads must be picked out. If the phase leads are to be 120 deg apart, the connection table and diagram give all the information necessary. Any job like this will show why the in-between slots can be

omitted from the connection diagram, and the diagram still provide the necessary information.

The slots for the leads should be marked with chalk before winding is begun; the bottom leads may then be stamped or tagged as the coils are wound in.

If this method of indicating the leads is not followed, the slots may still be located and marked after the coils are in by following the methods of counting slots and clips explained earlier. If only the top lead of a coil has been located, the bottom lead can be found with a test lamp. Short-pitch leads can also be found easily by using Table 9.

Rewinding Rotors with Standard-Lead Phase Coils

Phase Coils with Standard Leads

72. Consider a 3½-SPP winding for 8 slots and 8 poles having 6 conductors per slot. Assume that all coil leads are standard length. This combination of poles and phases gives 24 pole-phase groups. These groups require 48 phase coils, half of them right-hand coils and the other half left-hand coils, because more than two conductors per slot always means phase coils of both kinds.

All phase coils in this winding have standard leads, which are the simplest to handle. The proper use of standard-lead phase coils discussed here will help you understand the more complicated types of windings.

Table 7 shows that 12 of the 48 phase coils are the coils with phase leads: six are top-lead right-hand phase coils and six are bottom-lead left-hand phase coils. The remaining 36 phase coils are divided evenly into right-hand and left-hand phase coils.

Arrangement of Coils

73. Phase coils may be distinguished from plain coils by the amount and kind of insulation. This permits the phase coils in a winding to be separated from plain coils into the proper

number of groups. Two methods of arranging the coils before winding are possible, the straight-order method and the reverse-order method. For both methods the first step is to sort the coils into three piles: plain coils, right-hand phase coils, and left-hand phase coils.

The next step is to determine the coil grouping; that is, the number of coils per group and whether that number is odd or even. Table 8 shows 4 coils under phase *A*, 3 under *B*, and so on, that is, a 4-3-4-3 grouping. This information is necessary because phase insulation goes on the outside coil of each group, where a lead of one phase is next to or across the lead of another phase.

Straight-Order Method

74. For the straight-order method of arrangement of the $3\frac{1}{2}$-SPP winding under consideration, leave the coils in three piles, locate slot *1* in its proper relation to the slip-ring connection, and start the winding with a left-hand phase coil in that slot. Then continue in a clockwise, or right-hand, direction, putting one plain coil each in slots *84* and *83*. A right-hand phase coil in slot *82* completes the first 4-coil group.

The next group has three coils. Start it with a left-hand phase coil in slot *81*, and then put a plain coil – the only plain coil this time – in slot *80*. End this group with a right-hand phase coil in slot *79*. Then put in another 4-coil group, just like the first group. Follow it with another 3-coil group. Continue in this way until all coils are in; be careful with the partly filled slots.

In this straight-order method, the coils are picked from the proper pile as they are required. The repairman must be very careful to pick up the right kind of coil each time.

Reverse-Order Method

75. The reverse-order method of arrangement requires more care in laying out the coils at the start. For the odd

grouping in Table 8, instead of piling the coils in three groups, each consisting of the same type of coil, lay them out on a bench in the 4-3-4-3 phase groups just described. Pile each individual group in reverse order, however. In a three-coil group, put the last phase coil on the bottom, the plain coil on it, and then the first coil on top.

For the even grouping in Table 10, in which the grouping is 4-4-4-4, each group has four coils: one phase coil, two plain coils, and again a phase coil.

With either odd or even grouping, each group begins on the rotor with a left-hand phase coil and ends with a right-hand phase coil. Consequently, the piles on the bench, which are in the reverse order, begin with a right-hand phase coil and end with a left-hand phase coil. With the reverse-order method of arrangement, the top coil is always the next one to go into the slots.

As already mentioned, the complication of right-hand and left-hand phase coils comes only with more than two conductors per slot.

Rewinding Rotors with Short-Lead Phase Coils

Short-Lead Phase Coils

76. The most complicated type of a-c wave winding using large conductors must have short-lead phase coils. The mechanical stiffness of such conductors, which prevents bending the leads by hand during the final connecting, makes the short-pitch leads necessary and the complication of such coils unavoidable. Because of the many details which must be watched when winding such coils, it is desirable to have a thorough understanding of the winding of coils with standard leads before beginning to study the winding of coils with short-lead phase coils.

As an example, consider a 5-SPP winding for 150 slots and 10 poles, with 4 conductors per slot. Assume that the con-

ductors are so large that special SP short-lead coils must be used for some plain coils and for some phase coils. Use Fig. 15 and Tables 11 and 12 for checking the winding.

The winding has 30 pole-phase groups, each containing 5 coils. The phase coils come at the beginning and at the end of each group, so there will be $2 \times 30 = 60$ phase coils. Some of these coils have standard-length leads and some have short leads.

On a winding with large conductors, it is customary to use short leads for the main phase leads. On comparison of Tables 11 and 12, it is seen that all 12 phase leads belong to phase coils so that there will be 24 short-lead phase coils, or for each phase, 2 right-hand short-top-lead phase coils, 2 right-hand short-bottom-lead phase coils, 2 left-hand short-top-lead phase coils, and 2 left-hand short-bottom-lead phase coils. The rest of the phase coils, or 36 phase coils, have standard leads, or there will be 18 right-hand standard-lead and 18 left-hand standard-lead phase coils.

Table 11 shows four connections in each SP group. Since there are 4 conductors per slot in this winding, there will be, according to Table , 9 clips in each SP group. The clips connect short-lead coils, and therefore there are $9 \times 6 = 54$ short-lead coils. Each SP group has two phase coils, which means that $2 \times 9 = 18$ out of the 54 short-lead coils were already accounted for as phase coils. Therefore, there are actually only $54 - 18 = 36$ short-lead plain coils, or 18 short-top-lead plain coils and 18 short-bottom-lead plain coils.

Since the total number of coils is 150, the rest of the coils, or $150 - 60 - 36 = 54$ coils, are plain full-pitch standard-lead coils.

Arranging of Coils Before Winding

77. All the coils in this winding may be divided into three major groups, or nine different piles, as follows:

Group 1. 90 full-pitch or standard-lead, coils, consisting of

18 right-hand phase coils, 18 left-hand phase coils, and 54 plain coils.

Group 2. 36 SP, or short-lead, plain coils consisting of 18 short-top-lead coils and 18 short-bottom-lead coils.

Group 3. 24 short-lead phase coils, consisting of 6 short-top-lead right-hand coils, 6 short-bottom-lead right-hand coils, 6 short-top-lead left-hand coils, and 6 short-bottom-lead left-hand coils.

Start of Winding

78. The best way to start winding a short-lead job is to divide the coils into nine piles, as mentioned in the preceding article. Then select as slot *1* a slot that will permit a suitable connection to the proper slip ring. Mark this slot with chalk for the full width of the core. This mark will show the starting point of the winding and the A_1 lead coil, which is a left-hand short-bottom-lead phase coil.

Short-Bottom-Lead Coils

79. Next chalk on the core the slots for the rest of the short-bottom-lead coils. Mark these slots at the front, or collector-ring end, of the core.

The slots are found in the same way as the slots in SP groups, according to Fig. 15 and Tables 11 and 12. According to the rules explained earlier, the *SP-1* group is found by counting four slots back from the slot *1* for A_1, or slots *150, 149, 148,* and *147*. These slots contain short-bottom-lead coils for *SP-1*. In Table 12, these slots are marked *Z, Y, X,* and *W*.

The second group of short-bottom-lead coils comes at *SP-2*, ahead of the A_2 slot. The connection table, Table 11, puts the A_2 lead in slot *136*; the other leads are in slots *135, 134, 133,* and *132*.

The third group of short-bottom-lead coils is at *SP-3*, ahead of the B_1 slot. According to Table 11 the No. 1 lead is in slot *51*, and slots *50, 49, 48,* and *47* are for the SP leads. Simi-

larly, the fourth group, including the B_2 and the *SP-4* leads, lies in slots *36* to *32* inclusive.

The short-bottom-lead coils of the C phase, at C_1 and *SP-5* and C_2 and *SP-6*, are in slots *101* to *97* inclusive and *86* to *82* inclusive. The six groups of short-bottom-lead coils have now been located and marked.

Short-Top-Lead Coils

80. The next step is to find and mark the slots for the short-top-lead coils. These markings should be on the rear end of the core and should show where to put the bottom half of each short-top-lead coil. With all these markings correct, on front and rear, the repairman will pick up the correct slot as each coil is wound in. The bottom half of every coil is started first in the bottom of a slot.

To mark the slots for the short-top-lead coils, keep on using Fig. 15 and Tables 11 and 12. Start at *SP-1* on the diagram, which this time shows the required slots starting at the A_3 lead and going to the left of that lead. To find the slots for the bottoms of these coils, subtract the back pitch, $16 - 1 = 15$, from the A_3 slot, which for this armature is *132;* this gives slot *117* for the start. Mark this slot and the four slots to the left of it, slots *117* to *121* inclusive in all. At the other SP points do the same thing; that is, find the slot numbers for leads Nos. 3 and 4, subtract the back pitch, in slots, and each time mark the slot found in this way and the four slots to the left of it.

Actual Winding

81. After marking 60 slots at the front and rear ends of the core, start the actual winding in slot *1* with a short-bottom-lead left-hand phase coil. Then continue around the core counterclockwise, putting in three short-bottom-lead plain coils in slots *150*, *149*, and *148*. Slot *147* gets a short-bottom-lead right-hand phase coil.

From slot *147* to the slot at the left of the next marked slot, both right-hand and left-hand full-pitch coils are used, with plain coils filling out the groups. Merely follow the diagram and the slot markings, paying close attention to the slot markings as well as to the proper coil for each successive slot.

Winding Odd Groups

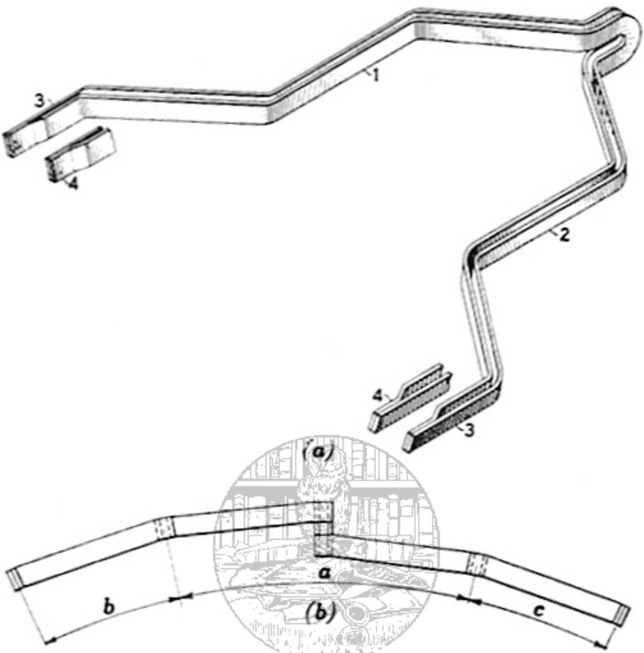
82. The preceding articles have discussed the winding procedure for even groups of short-lead coils. In the winding of odd groups, special attention should be given to the fact that alternate groups contain a different number of coils. An example is a 12-pole 126-slot three-phase winding with $3\frac{1}{2}$ SPP and 4 conductors per slot. Tables 7 and 8 and Fig. 13 apply to such a winding. This winding will have $6 \times 12 = 72$ phase coils, half of them right-hand coils and half left-hand coils. In addition, some of the phase coils and plain coils will have short leads. As already explained, the coils for this job should be divided into nine piles and three groups, as follows:

Group 1. 96 standard-lead coils, consisting of 24 right-hand phase coils, 24 left-hand phase coils, and 48 plain coils.

Group 2. 6 short-lead plain coils, consisting of 3 short-top-lead coils and 3 short-bottom-lead coils.

Group 3. 24 short-lead phase coils consisting of 6 short-top-lead right-hand, 6 short-bottom-lead right-hand, 6 short-top-lead left-hand, and 6 short-bottom-lead left-hand phase coils.

In the odd grouping, special care is needed to keep the proper grouping throughout the winding. One way to keep an accurate check on the coil grouping is to mark the first and last coil of each group with white chalk. Mark the coils on the top rear diamond point, the center of the rear end of the coil, and then proceed with the winding following the diagram and tables.



1. top coil side
2. bottom coil side
3. coil leads
4. short leads

(a) Two-strap coil
(b) End view

FIG. 20. COIL FOR A-C WAVE WINDING

Placing Coils into Slots

Shape of Coil

83. Coils for a-c wave windings are normally of the shape shown in Fig. 20*(a)*. The coil shown is made of two straps with spacers between the straps. The top side *1* and the bottom side *2* of the coil are in one piece at the back of the coil, and end in leads *3* at the front. Short leads *4* are shown separately and are used for heavy conductors. The end view *(b)*

shows the spread, or winding pitch, of the coil. The back pitch is a, the pitch of the top lead is b, and the pitch of the bottom lead is c. The winding pitch for the coil is $a + b + c$. Exact pitches are of great importance; the allowable tolerances in the forming of coils are small.

Coils for a-c wave windings are of either the one-piece or the two-piece type. The two-piece coil has its rear ends connected after winding. This coil is somewhat easier to wind into the slots than the one-piece coil, but the extra soldered figure-8 connectors at the rear offset this slight advantage, so that the one-piece type is more common.

Most strap coils for a-c wave windings have the conductors insulated separately; hence, a single strap may be fed through the slot opening at a time.

Initial Coil Insulation

84. The insulation materials dealt with here and in the following articles are those most generally used for Class A insulation. The various insulation materials for the different classes were covered in Part 1 of this text. Insulation materials used for the repair or rewinding of rotors should be as good or better than the materials originally used for the rotor. If in doubt, consult the motor manufacturer about the materials used.

To insulate the bare copper strap after it has been formed, the ends are taped and the slot sections are wrapped with sheet material and then taped. This insulation is called first insulation of the coil because it is applied to the coil before the coil is placed in the slot. Table 13 lists the materials and layers for the end insulation, the coil-side wrappers, and the finish tape.

The first end insulation, for both plain and phase coils, is tan-colored treated-cloth tape; only low-voltage (up to 60-volt) plain coils omit this insulation. A lay of one means an overlap of one-half in the winding, which gives a total thickness of

TABLE 13

FIRST INSULATION ON COILS FOR A-C WAVE WINDINGS

Voltage	Insulation on Ends: 0.010-in. Treated-Cloth Tape		Coil Wrappers: Turns of 0.012-in. Mica and Fish Paper	Finish Tape: 0.007-in. Cotton Tape	
	Plain	Phase		Ends	Slots
Up to 600		1 lay	1½	½ lap	Spaced
Up to 1200	1 lay	2 lay	2½	½ lap	Spaced
Up to 2400	2 lay	3 lay	3½	½ lap	Spaced

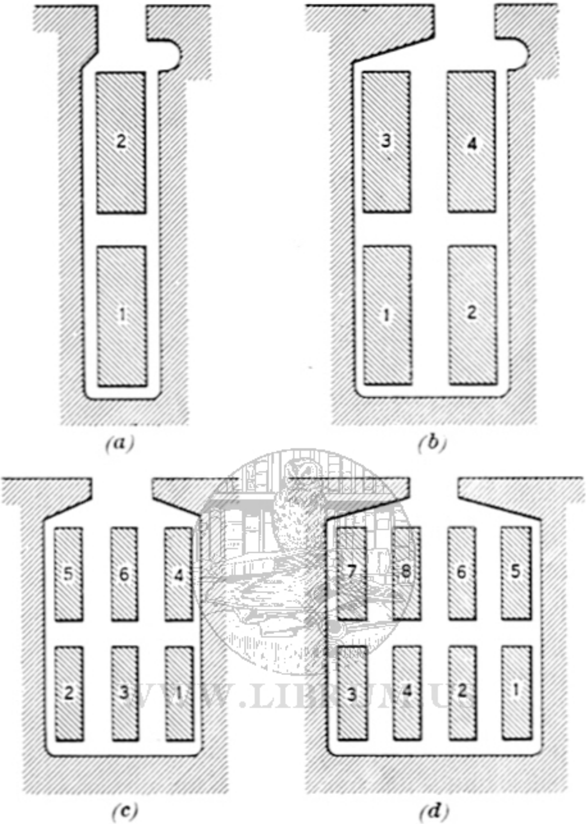
two layers; a 2-lay winding has a total thickness of three layers, and so on.

The wrapper for the slot section of the coil is cut from a mica-and-fish-paper sheet 0.012 in. (inch) thick. The grain of this material, if there is any, must run parallel with the length of the coil wrapper, which is equal to the straight part of the slot section. This wrapper, when wound on, begins at the lower edge of one side of the strap and ends at the top edge of that same side, after making one, two, or three full turns as the table specifies, plus a half-turn overlap. When more than a turn and a half is required, the ends of the first full turn are tapered slightly, not more than ¼ in. at each end of the finish edge.

The finish tape is standard cotton, 0.007 in. thick. On the ends of the coil it has a lay of one, or a half lap. Over the slot portion it is merely spaced.

Varnish Treatment

85. For the 600-volt and 1200-volt class, the varnish treatment is one dip and bake for the unwound coils and another for the entire rotor after the winding has been put into place. For a 2400-volt rating the coils are dipped and baked twice and the wound rotor once. For all voltages, the finished winding should be sprayed with a good air-drying varnish.



1 to *8*. conductors

(*a*) Two conductors per slot
(*b*) Four conductors per slot
(*c*) Six conductors per slot
(*d*) Eight conductors per slot

FIG. 21. SLOTS FOR A-C WAVE WINDINGS

Baking

86. The time and temperature for baking varies with the varnish used and with the diameter of the rotor. Usually, however, 4 to 6 hr (hours) at 110 C (degrees centigrade) will be satisfactory for strap coils. For completed rotors, use a tem-

perature of 115 C to 125 C. Then bake 12 hr for rotors up to 15 in. in diameter, and 24 to 36 hr for 15-in. to 25-in. rotors.

Types of Rotor Slots

87. Rotor slots for a-c wave windings are partly closed, as shown in Fig. 21, *(a)* to *(d)*. This illustration gives front views of the slots on top of the core, showing how the slots look from the slip rings.

Which of the four main types of rotor slots is selected depends largely on the number of conductors per slot, which may be 2, 4, 6, or 8. The shape and size of both the slot itself and its opening are important in determining how coils should be fed into the slot.

Two Conductors per Slot

88. A slot with two conductors is shown in Fig. 21*(a)*. In such a slot the opening is centered and there is only one way to insert the coils: the bottom conductor *1* goes in first, then the top conductor *2*. The conductors in Fig. 21 are numbered in the order in which they are placed in the slot. When conductors are taken out of the slot for repair, the sequence is, of course, reversed, and the conductor with the highest number in Fig. 21 comes out first while the conductor *1* comes out last.

Four Conductors per Slot

89. Four conductors per slot require an overhung slot, as shown in Fig. 21*(b)*. The straight side of the slot is usually placed so that the inside strap of the top coil comes against that side.

The words *outside* and *inside*, as used here, refer to the coils and not to the slots. Hence, the inside conductor of a bottom coil is not on the same side of the slot as the inside conductor of a top coil, because the bottom and top conductors in the same slot come from different coils.

In winding one-piece coils having four conductors per slot into the overhung type of slot, the inside bottom left-hand

conductor *1* is fed in first, and then the outside bottom conductor *2*. With the top conductors, the outside conductor *3* is fed in first and pushed over to its place. The inside top conductor *4* then slides easily down the straight side of the slot. In repair work, such conductors come out in the reverse order. As mentioned in Art. 45, the top, or right-hand, lead from this slot is taken from the top right-hand conductor *4*, and the bottom left-hand lead from the bottom left-hand conductor *1*.

Six Conductors per Slot

90. When there are six conductors per slot, as in Fig. 21*(c)*, the slot opening is centrally located. The outside bottom conductor *1* is put in first, then the inside conductor *2*, and finally the middle conductor *3* is driven in. The inside conductor *4* of the top coil side is usually put in first because the pull of its other side, already in a slot as a bottom conductor, drags it into place. Then the outside conductor *5* is forced in and over, after which the middle conductor *6* is driven in.

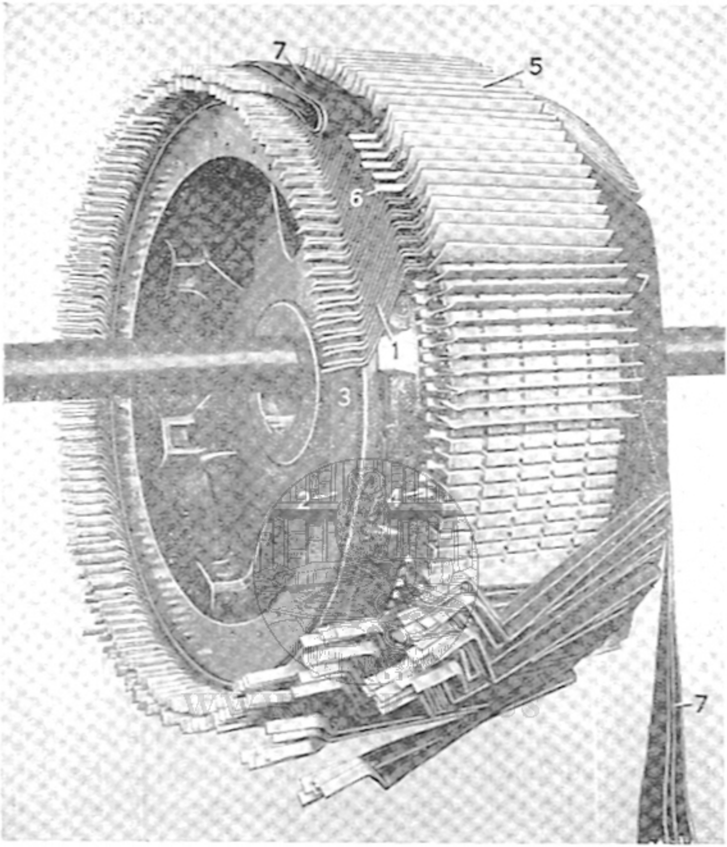
Usually, the middle conductor can be started at the rear end. If the drag of the end connection of the one-piece coil causes too much trouble, start this conductor in at the front end.

Eight Conductors per Slot

91. When there are eight conductors per slot, as in Fig. 21*(d)*, the slot opening is centrally located. The outside bottom conductor *1* is put in first, then the second half *2* of the outside pair. Next, the inner half *3* of the inside pair is fed in and pushed over against its side of the slot. Finally, the other half *4* of the inner pair is driven in.

The procedure for inserting the top conductors is much the same; they are inserted in the order *5*, *6*, *7*, and *8*.

The order of insertion of straps given in the foregoing instructions takes full advantages, as far as is possible, of the pull of the coil.



1. coil ends
2. coil support, or ring
3. exposed ring metal
4. slot insulation
5. winding cell
6. fiber separator
7. end insulation

Fig. 22. Winding Insulation of Wave-Wound Rotor

Winding Insulation

92. Although all coils used in a-c wave windings for rotors are preinsulated, such insulation is little more than a first coating. The core, the slots, and the end windings must have more insulation. This extra insulation, put on during the wind-

ing operation, is called the winding insulation, and consists of the core insulation, the slot insulation, and the winding cells.

Core Insulation

93. A rotor in the process of winding and insulating is shown in Fig. 22. The coil ends *1* rest on a support *2*, sometimes called a coil ring. Such supports vary in type, and the methods of insulating them also vary. Most types use treated fullerboards, held in place with tape or canvas hoods, for the filler. The chief points to check are the thickness of the insulating wall and the overhang, or creepage distance, of the exposed ring metal *3* to the winding.

Slot Insulation

94. Slot insulation in the form of a fiber strip *4*, Fig. 22, is placed in the bottom of the slot and under, not inside, the winding cell *5*. Each strip should be at least $\frac{1}{2}$ in. longer than the winding cell and should project at least $\frac{1}{4}$ in. past each end of the cell, as shown. Because of its length and position, this bottom strip prevents tearing and cracking of the cell during the winding process. Because of its thickness, it also tends to keep a high lamination or a heavy burr that may get by inspection from cutting or chafing through the insulation proper after the slot wedges have forced the coils against the bottom of the slot.

Winding Cells

95. Winding cells are usually made from fish paper 0.010 to 0.015 in. thick, the exact thickness depending upon the amount of room in the slot. Thick cell paper clogs up the narrow slot opening, making it difficult to feed in the copper straps. Hence thin cells, paraffin treated, are most satisfactory; additional fillers may be put in the slot between the core and the cell or between the straps. The cells should project at least 2 in. above the core, since with a shorter projection, the part sticking out is stiffer and more difficult to handle.

Fiber Separators

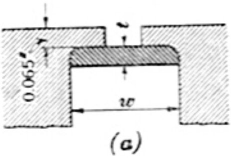
96. A fiber separator, such as shown at 6 in Fig. 22, should be placed between the coils in the slots. Cut it long enough to cover the full length of the top slot section of the coil, and wide enough to make a snug fit across the slot. The length of this strip is important, because in most windings the top and botom slot sections are of different lengths and the longer one tends to rest on the ends of a coil in the next slot. This contact always comes at a point where the pads of insulation between the layers of coil ends are hard to apply and still harder to place accurately. Push this separator through the slot from one end, tilting it enough to slide in easily, and then drive it flat with a T-slot drift.

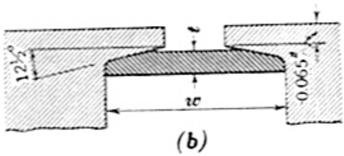
Fillers

97 Side wedges are called fillers, to distinguish them from the main wedges at the top of the slot. Fillers are cut from fish paper, fullerboard, or fiber. After the conductors have been driven down, side fillers are used to lock them in place widthwise. Locking the bottom conductors in place at once leaves more room for handling the top conductors and also keeps the bottom ones from falling out, especially from the under side of the core. Driving down and locking the top conductors gives the clearance necessary for the top wedges; all conductors must be below the point where the overhang of the tooth starts. Consequently, it is important to lock the bottom conductors and wedge the tops as the winding progresses.

Cell Closing

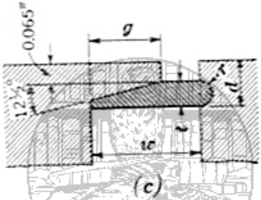
98. To protect the insulation on the conductors, the cells are trimmed with margin enough to give a safe overlap on top of the coils. All fillers for a given slot should be in place before the cells are trimmed and folded. After the cell ends are turned over, a thin fiber strip is placed on top. This strip serves as a slide for the wedges, preventing them from catching and





w	t
Up to ½	1/16
Up to ¾	3/32

w	t
0.300 to 0.500	1/16
0.500 to ⅝	3/32
⅝ to ⅞	⅛
More than ⅞	5/32



w	t	d	r	g
Up to 0.440	1/16	0.125	0.040	5/32
0.440 to 0.500	3/32	.160	.048	7/32
0.500 to 0.750	⅛	.190	.063	9/32
More than 0.750	5/32	0.225	0.080	7/16

(a), (b), (c) Wedges for three types of slots

FIG. 23. DIMENSIONS OF WEDGES

tearing the cells as they are driven in. It should be in one piece and should be double the length of the wedge. In fact, it may well be cut an inch or so long and trimmed later. The extra length will take care of any slippage as the wedge is started and will also protect the coils from the wedge-driving tool.

Wedges

99. After the winding cells have been trimmed and turned

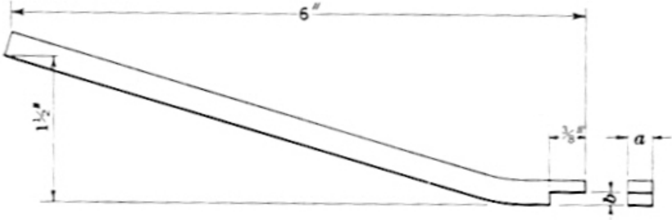


FIG. 24. DIMENSIONS OF WEDGE-DRIVING TOOL

over on top of the coils, fiber wedges are driven in. Where a tight fit is necessary, a piece of fiber is first placed between the wedges and the coils. The wedges are usually made in two pieces and are driven in from each end of the core. A one-piece wedge is often used for short cores. A tighter fit for every core can always be obtained with two-piece wedges.

The wedges for wave windings in a-c machines are of three general types. Both the shape and the thickness of the fiber wedges depend on the type of slot, its size, and the weight of the coils. Three types of slots and their wedges are shown in Fig. 23, *(a)*, *(b)*, and *(c)*. Suitable dimensions for the wedges, in inches, are included in Fig. 23 in tabular form. The maximum thickness of the wedge is indicated by t, and the width of the slot by w. The letter r stands for the radius of the rounded end of the wedge in *(c)*. The two dimensions d and g are self-explanatory.

The wedge should be longer than the slot. For a wedge thickness of $\frac{3}{32}$ in. or less, the extra length should be $\frac{1}{2}$ in.; for a wedge thickness of $\frac{5}{32}$ in. down to $\frac{3}{32}$ in., the extra length should be $\frac{3}{4}$ in. The wedge should overhang the same amount at each end, $\frac{1}{4}$ and $\frac{3}{8}$ in., respectively, for the lengths considered.

The tool for driving wedges into rotor slots is made from cold-rolled steel of any cross section available, and is bent and undercut, as shown in Fig. 24. Its shape helps it to clear end windings and prevents damage to coils. The width a of the

driving face should be less than the width of the slot opening, and the depth *b* should be less than the thickness of the wedge. The lip of the tool is merely a guide.

The proper wedging of strap-wound rotors is highly important. In a good finished job, the insulation in the ends of the slots is undamaged because the repairman used care in driving in the wedges. The entire job is neat and the wedges fit the spaces left for them.

End Insulation

100. Insulating material between the top and bottom layers of coil ends is called end insulation. It has two major functions: to insulate between the coil ends that cross one another, and to fill the space between layers so as to prevent sagging of the coils under band pressure.

The material commonly used for end insulation is treated duck, about 0.030 in. thick. This material has had three varnish treatments. Another material is varnish-treated asbestos cloth about 0.045 in. thick. The asbestos will stand higher temperatures than the treated duck and will not shrink.

The material selected for end insulation is wound on in long strips such as shown at 7 in Fig. 22. In width, this material must run from the clip or the coil end to the end of the fiber strip between the coils in the slot.

Two or more strips of end insulation are used, each successive outer strip being wider than the one underneath it. The result is a stepped pad. The thicker edge of these pads is against the clips at the clip end, and against the ends of the coils at the coil ends. The object of the steps is to fill the tapered space for its full length, so as to provide a solid bed for the end bands.

Connectors for Wave Windings

Connectors or Clips

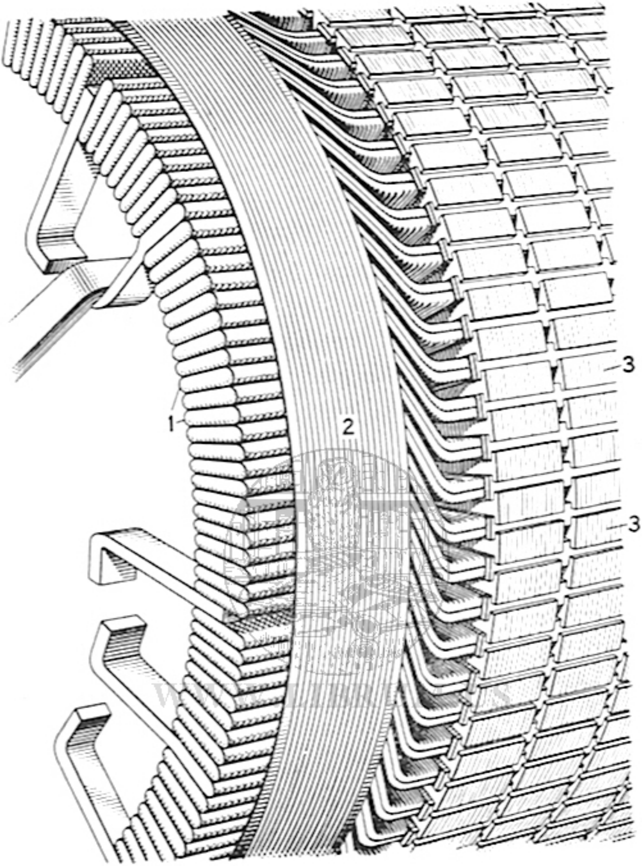
101. The top and bottom layers of coil leads must be connected electrically at the proper points. But at the same time, the ends of the coils must be separated mechanically, because if the band wire should press them together, the copper strap would most likely chafe or cut through its insulation at some point. Such a fault might well short-circuit several coils. Tinned copper spacers at the joints keep the layers of heavy leads apart. Loops of copper, called connectors or clips, slipped over the leads and their spacers, connect them. Each joint is soldered.

If a spacer is too thin, or if it is left out, insulation cutting is likely to follow unless the conductor is light. As you can see from this example, constant attention to details is necessary to avoid trouble.

When the copper strap is light and dead soft, spacers may be omitted. To give proper clearance for the coil ends, the connectors are then squeezed together in the middle, forcing the straps away from the center of the clip. The clips then look like a figure 8, and are called figure-8 clips. The figure-8 clips that join the coil ends are soldered with either a half-tin and half-lead solder or a solder having a high tin content. The high-tin solder, which is properly called a lead alloy of tin rather than a solder, is used when the joints must withstand high temperatures, or must be extra strong. The tin alloy has a more critical melting point than half-and-half solder. It does not soften until its temperature is near its melting point; once at that point, it quickly becomes fluid.

Wedging Figure-8 Clips

102. In order to make a tight joint, all figure-8 connectors should be tightened with wooden wedges before they are soldered. Using maple or other hard wood, cut the wedges on



1. insulation caps
2. band insulation
3. wedges

FIG. 25. INSULATION OF CLIPS AND BAND

a taper to fit the space between the clips. Each wedge should be wide enough to cover the clips it presses against, and a half inch longer at each end. Drive the wedges in a little at a time until the whole circle of coil ends is arch bound. Leave the wedges in place until the excess metal in the coil ends has been machined off.

Clip Insulation

103. A finished winding is shown in Fig. 25. The insulation for the clips consists of caps, or bags, *1* made of 0.017-in. drill, which is a tough cloth. Each bag is dipped in varnish and pulled over a clip while wet. Two or more such bags are needed for each clip. The number of caps depends upon the maximum standstill voltage between the slip rings, and upon the space between adjoining clips. A few turns of thin cotton tape tie the mouth of each bag tight around its straps, inside the clip.

Clip insulation is applied before the band wire. The band insulation *2* in the illustration has been brought over close to the clip insulation, as it should be. The front band and its insulation should be kept out toward the leads, as shown here, both in order to hold the leads solid and to cover rough edges. (This illustration shows plainly the wedges *3*.)

Banding and Band Insulation

Recording Old Band Data

104. When stripping a rotor for repair or rewinding, the first step is to remove the bands. It is important to make a record of the following details: size of wire; number, or total width, of turns, or both; number of layers of wire, whether each band is in one piece or is insulated into two or more sections; number and spacing of clips; material of the band wire and its clips, whether steel or nonmagnetic material, such as bronze; width of the insulation under the bands; total thickness of band insulation, or thickness of material and number of layers; material or combination of materials forming the band insulation; and location of each band in reference to the core, clips, or rear coil loops.

This list of items may seem long. The details mentioned, however, are important and must be given careful consideration to insure a good tight job in rewinding the rotor. In fact, success in winding rotors and armatures can come only with

close attention to details. As the winding is stripped, the insulating and filling material and its position between layers, or coil supports, and so on should be carefully checked. A good winding job must be correct mechanically as well as electrically.

Band Insulation

105. The insulation under the wire bands should extend at least $\frac{3}{8}$ in. past the last turn of wire, on each side of the band, to insure proper creepage distance. An extension of $\frac{1}{2}$ in. or more is even better. In general, two layers of 0.012-in. mica and fish paper are sufficient band insulation, but each winding should be checked individually for its voltage requirements and for the type of band insulation it needs. The band and its insulation at the rear end are kept well over toward the rear coil loops.

Because all bands are soldered completely for their full width and circumference, the insulation selected should not char or ooze varnish into the band under the heat of soldering. The common insulation materials are mica and fish paper, treated duck, treated asbestos cloth, or combinations of these materials.

Band Clips

106. Steel clips, well-tinned, should be placed under the bands. These clips should be $\frac{3}{8}$ to $\frac{1}{2}$ in. wide, 0.012 or 0.022 in. thick, and long enough to permit at least $\frac{1}{2}$-in. turnover on top of the band at each end. The clips should be spaced about 4 slots apart, and 3 clips close together are needed where the band starts and stops.

Size of Banding Wire

107. The necessary diameter of the banding wire and the number of turns per band, which together make up its width, depend upon the weight of the coil ends and the peripheral, or surface, speed of the rotor. The bands, rather than the slot wedges, should keep the coil ends in place.

TABLE 14

SIZE OF BANDING WIRE AND ALLOWABLE TENSION

Diameter of Rotor in.	Diameter of Banding Wire in.	Maximum Banding Tension on Wire lb	
		Kind of Rotor Coil	
		Wire or Ribbon	Strap
Up to 10	0.029	80	80
10 to 15	.045	200	200
15 to 24	.064	250	400
24 and above	0.081		550

Table 14 gives the diameter of the banding wire and the proper tension for various sizes of rotors wound with different kinds of coils. Where it can be used, 0.064-in. wire is best for all rotors up to the 24-in. size. Banding tension is the pull, in pounds, on the wire during the banding process. A banding machine to apply this tension can be purchased at small cost. The third column of the table gives the maximum permissible banding tension for a rotor that has coils of wire or light ribbon; the last column is for coils of strap or heavy ribbon. Note that the banding tension depends primarily on the size of the band wire rather than on the size of the rotor.

The number of banding wires for a rotor should be enough to keep the maximum tension per wire, with the machine in service, from 20 to 30 percent lower than the allowable banding tension for that same rotor given in Table 14. The proper size of wire for any given band is partly a matter of judgment, based on the type of winding and the total band tension. In general, the band should cover about 60 percent of the coil ends, and the size of wire should permit this while still giving the total strength required.

Rotor banding should have a reasonable margin of safety at overspeeds, to avoid danger of breakage. It should be applied at not less than the maximum tension reached at overspeed,

chiefly to prevent, as far as possible, any movement of the coils. An in-and-out movement especially chafes the coil insulation, causing in time a ground or a short circuit. Another reason for high banding tension is to test the band wire for weak spots as it goes into place.

Band-Stress Calculations

108. The formula for the stress in each band is

$$S = 2.261WD\left(\frac{R}{1000}\right)^2$$

in which S = total stress on the band, in pounds
W = total weight of the coil ends, including insulation and banding, in pounds
D = diameter of rotor, in inches
R = rated speed of the rotor, in revolutions per minute

EXAMPLE 1. A rotor 8.5 in. in diameter (a small rotor) and in the light-ribbon class is to run at 5000 rpm (revolutions per minute). The total weight of the copper plus insulation plus banding on each end is approximately 10 lb (pounds).

Assuming 0.064-in. wire, calculate *a*) the stress in each end band, *b*) the minimum number of turns in each band, and *c*) the approximate width of each band.

SOLUTION. *a*) The stress in each end band

$$S = 2.261 \times 10 \times 8.5\left(\frac{5000}{1000}\right)^2 = 4800 \text{ lb (approx.)} \quad \text{Ans. } (a)$$

b) For 0.064-in. wire the winding tension, from Table 14, is 250 lb. The highest stress in service should be held down in the calculations to 70 percent of this value, or 175 lb per wire. Then the number of turns in each band should be at least $\frac{4800}{175} = 27.5$, or 28. Ans. (*b*).

c) The width of each band will then be $(28 \times 0.064) + (2 \times 0.012) = 1.82$ in. (approx). Ans. (*c*).

The addition of 2×0.012 is for the band clips, and is twice their thickness. The value 1.82 in. is the smallest width needed for

strength alone. If it is so narrow that too much of the coil ends will lie outside the band unsupported against centrifugal force when the rotor is up to speed, make the bands enough wider to take care of that factor. Judgment based on examination of other rotors is about the only guide here.

EXAMPLE 2. A rotor 17 in. in diameter (a large rotor) is to run at 2070 rpm. The weight of copper plus insulation plus banding on the rear end of this rotor is approximately 84 lb. *a*) Calculate the stress in each end band at 2070 rpm. *b*) Consider that strap coils are used for rotors more than 15 in. in diameter, and refer to Table 14 to determine the size of banding wire for this job and its permissible maximum banding tension. Then, assuming an allowable service stress of 70 percent of this maximum, determine the number of turns in each band and the width of each band.

SOLUTION. *a*) The stress in each end band at 2070 rpm will be

$$S = 2.261 \times 84 \times 17\left(\frac{2070}{1000}\right)^2 = 13{,}850 \text{ lb (approx.)}. \quad \text{Ans. } (a)$$

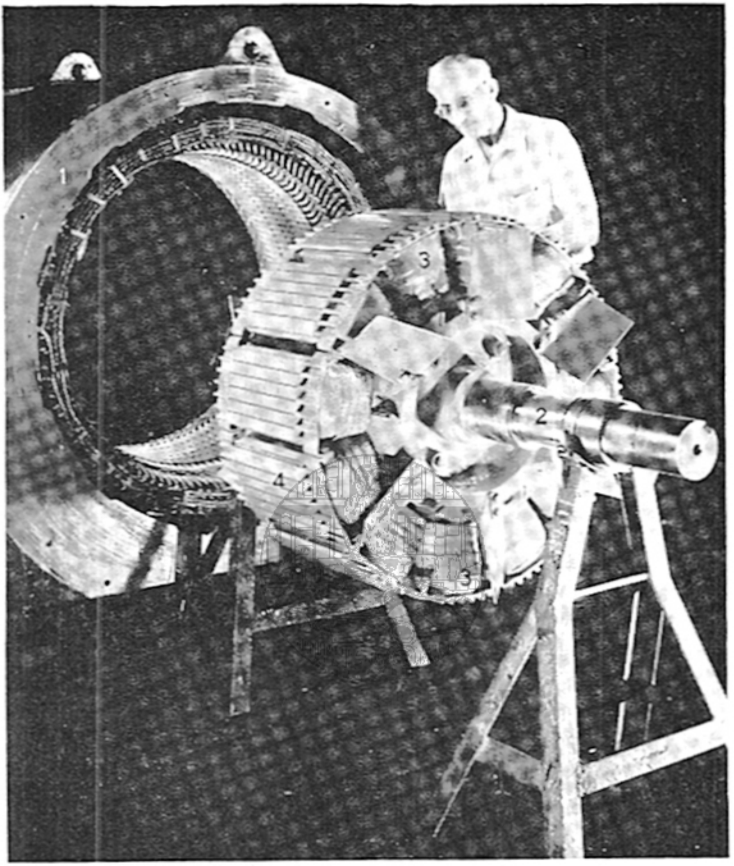
b) Table 14 shows that 0.064-in. wire should be used for this job, with a permissible banding tension up to 400 lb pull for strap coils. The allowable service stress is then 70 percent of 400 lb, or 280 lb per wire. Then the number of turns in each band should be at least $\frac{13{,}850}{280} = 49.49$, or 50. The width will then be $(50 \times 0.064) + (2 \times 0.022) = 3.25$ in. The heavier wire should have the heavier clips Ans. (*b*).

Synchronous Motors

Construction of Synchronous Motor

109. The synchronous motor is a special type of a-c motor used when a large-sized motor which operates at a constant speed is needed. The construction of synchronous motors differs from that of a-c induction motors, and is similar to that of a-c generators.

A synchronous motor in a repair shop is shown in Fig. 26. The stator *1* contains a three-phase winding to which the a-c line voltage is applied. The rotor *2* contains salient poles *3*



Courtesy of Allis-Chalmers Manufacturing Company

1. stator
2. rotor
3. salient poles
4. squirrel-cage winding

FIG. 26. SYNCHRONOUS MOTOR

whose windings are energized by direct current to keep the rotor in synchronism, or in step, with the synchronous speed. At the start, however, the windings are not energized by any outside source. The rotor would not be able to start revolving if a squirrel-cage winding *4* were not added to the faces of the poles. The current induced in the bars of the squirrel-cage

winding cause the rotor to start revolving much like the rotor of an induction motor. When the rotor comes up to speed, direct current is applied to the pole windings and the motor keeps rotating at a constant speed.

Repair of Synchronous Motors

110. The rewinding, insulation, and connection of coils in synchronous motors follow the pattern for other rotating machines. The d-c poles of a synchronous motor are handled much as the field winding on d-c machines is handled, and the stator winding of a synchronous motor is handled much as the rotor winding of induction motors is handled.

Specific problems arise with the squirrel-cage winding. This winding is used for starting and to prevent sudden changes in speed while operating under load. If an open circuit or a high-resistance connection appears in this winding, it means that the starting torque is reduced. Either of these faults on a synchronous-motor rotor may cause sparks that can be seen by the operator if the winding is not enclosed. The machine should then be shut down and a careful inspection should be made for a loose or burned bar in the squirrel-cage winding.

During the starting period, the field circuit of the motor should be closed through a low resistance. The field-discharge resistance is often used for this purpose. If an open circuit should occur in the discharge resistance, a very high voltage will be induced in the field circuit; this voltage may be high enough to cause an arc across the collector rings or from terminal to terminal. When such an arc is observed, shut down the machine, inspect the field coils and test for an open circuit.

Synchronous-Motor Trouble Chart

111. Troubles common to synchronous motors are listed in the trouble chart in Table 15. The possible causes of the trouble are given and the methods of making the necessary repairs are indicated

TABLE 15

TROUBLE CHART FOR SYNCHRONOUS MOTORS

Trouble	Cause	Remedy
Will not start	Power off; one phase off	Check main switch; test with lamps or voltmeter; restore power
	Low voltage, one or more phases	Check line voltage with voltmeter; restore proper voltage
	Blown fuse	Test fuses; replace blown fuse and restart
	Overload-relay operation	Inspect; reset relay and restart
	If push button or remote control, open in control circuit	Inspect push button and overload-relay contacts; test holding coil for open circuit; check for open circuits; repair
	Excessive load	Check that driven equipment is unloaded; disconnect or reduce starting load (Note: Synchronous motors will not start with excessive load unless special equipment is provided.)
	Open circuit or high resistance in squirrel-cage winding	Inspect squirrel-cage winding for loose or broken connections; repair
	Field energized	Check starting setup; restore to normal and restart
	Open armature lead	Hold in starting position; check for single-phase

TABLE 15 – Continued

Trouble	Cause	Remedy
	Defective motor leads or motor windings	Inspect motor and motor leads; test for defective insulation; repair
	Bearings stiff or frozen	Inspect bearings; if possible, bar over by hand; replace oil or grease
2. Motor starts but does not come up to speed	Low or unbalanced voltage	Check voltage; restore normal voltage
	Wrong armature connections	Check connections; make proper connections
	Excessive load	Reduce starting load
	Field energized at start or before motor has reached proper speed	Check starting setup; restore to normal
3. Motor does not pull into step	Field not energized; field current too low	Check excitation source for proper voltage and connections; check field switch, field rheostat, and slip rings and brushes for high resistance or open circuit; if necessary, shut down and test motor field circuit for continuity
	Excessive load	Reduce starting load
4. Overload device operates or fuses blow when load is applied	Field current too low; field current too high	Check for proper field current; adjust to near unity power factor
	Low or unbalanced a-c voltage	Check voltage; restore to normal
	Excessive load	Reduce load

TABLE 15 – Continued

Trouble	Cause	Remedy
5. Excessive hunting by motor	Excessive fluctuations in load	Reduce or balance loads; inspect and adjust loading devices
	Open or high resistance in squirrel-cage winding	Inspect squirrel-cage winding; repair
6. Motor overheats	Overload	Reduce load
	Excessive field current	Reduce field current to near unity power factor
	Low or excessively high voltage	Check for proper voltage; restore to normal
	Poor ventilation	Increase or cool ventilating air
7. Bearings overheat	Lack of oil or oil rings not turning	Check oil level; add oil if necessary; start rings; if rings will not turn, shut down and repair
	Worn or cracked ball or roller bearings	Shut down and inspect; repair

A-C Motor Repair

Serial 6631B PART 2 Edition 1

Examination Questions

Notice to Students.—Study this instruction text thoroughly before you answer the following questions. Read each question carefully and be sure you understand it; then write the best answer you can. If the answer involves a mathematical solution, show enough of your work to indicate how you obtained your answer. We will not accept answers alone. When you complete your work, examine it closely, correct all the errors you can find, and see that every question is answered; then mail your work to us. DO NOT HOLD IT until another examination is ready.

1. In what way is the wave winding of an a-c induction motor different from the *a)* wave winding of a d-c motor? *b)* lap winding of an a-c motor?

2. How can you tell at first glance whether a rotor is of the squirrel-cage or the wound type?

3. Why is a three-phase rotor preferred to a two-phase rotor even with a two-phase stator?

4. Why are one-piece coils more used in wave windings than two-piece coils?

5. A 63-slot rotor is available for a three-phase 6-pole motor.
   a) What will be the number of slots per pole per phase if wave winding is used?
   b) Will the rotor be suitable for this motor?
   c) Why?

6. How can the surface of a worn keyway or shaft be built up?

7. Why are some short pitches necessary in a-c wave windings?

8. What faults on a lap-wound rotor may be determined by a balance test?

9. In a wave winding with $4\frac{1}{2}$ SPP, how many slots are in the *a)* winding pitch? *b)* back pitch? *c)* front pitch? *d)* short pitch?

10. When placing a new ring in a squirrel-cage winding, what precautions should be taken to secure the original full-load speed?

11. A 144-slot 24-pole three-phase rotor winding has 2 SPP Give four other combinations of poles and slots per pole per phase that can be used with this rotor.

12. An a-c motor is provided with a rotor having a diameter of 18 in.
    a) What size banding wire should be used?
    b) What tension should be applied to this banding wire during its application if strap conductors are used?

13. A wave-wound rotor with 144 slots has been selected for a 12-pole motor.
    a) Write down the numbers of the slots from which the phase leads for phase B emerge.
    b) Write down also the numbers of the slots which contain phase coils for phase *B* if four conductors per slot are used.

14. During the test of a rotor with completed wave windings but with free phase leads, the tester has determined an open circuit between leads B_1 and B_4, a closed path between C_4 and $C_{\cdot}$, and an open circuit between A_3 and A_4.
    a) What do these findings indicate to the tester?
    b) Why?

15. The wave-wound rotor for a 10-pole motor has been brought to the repair shop. The winder has determined that 2 conductors per slot are used and has identified the bottom lead A_2. He then counts 4 clips between A_2 and the next free top lead on one side and 10 clips to the next free top lead on the other side.
    a) What is the SPP value for this rotor?
    b) Explain the method you used to find the SPP value and prove the result by another method.
    c) What is the total number of slots in the rotor?

Answer the following questions by giving the number of the question and the letter indicating the answer that you think is the correct one. Do not write out the answer.

16. A synchronous motor is brought to a repair shop with the complaint that it does not pull into step. The repairman knows that the reason is
    A. unbalanced and too low a voltage.
    B. high resistance in the squirrel-cage winding.
    C. too low a field current.
    D. wrong armature connections.

17. If a squirrel-cage rotor is very noisy and hot during motor operation, an experienced repairman will know that the rotor has a
    A. ground.
    B. loose connection.
    C. short circuit.
    D. wrong coil connection.

18. The winding insulation used on coil rings is considered a part of
    A. core insulation.
    B. slot insulation.
    C. winding cells.
    D. end insulation.

19. Specially prepared short leads on phase coils are necessary only when
    A. the coils are large and heavy.
    B. SPP is fractional.

C. the coils are of the right-hand type.
D. the short pitch is not used.

20. If a 3-SPP winding with 24 poles is to be rewound for 26 poles, the new rotor should have
A. 20 slots.
B. 224 slots.
C. 234 slots.
D. 252 slots.